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EVOLUTIONARY SPACE STATION FLUIDS MANAGEMENT STRATEGIES

CONTRACT FINAL REPORT

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FOREWORD

This report was prepared by General Dynamics Space Systems Division (GDSS) under NASA-Lewis Research Center Contract NAS3-25354, Task Order Number 002.

This report provides a comprehensive overview of the study results, which were obtained between November of 1988 and August of 1989.

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LIST OF ACRONYMS

ACC	- Aft Cargo Carrier
ACEM	- Attitude Control Enhancement Module
ACS	- Attitude Control System
ALS	- Advanced Launch System
ASE	- Airborne Support Equipment
ASTROMAG	- Astrophysics Magnet Facility
AXAF	- Advanced X-Ray Astrophysics Facility
BDM	- The BDM Corporation
CASR	- Comet Atomized Sample Return
CDR	- Critical Design Review
CELV	- Commercial Expendable Launch Vehicle
CER	- Cost Estimating Relationships
CETF	- Congressional Evaluation Task Force
CF	- Collapse Factor
CG	- Center of Gravity
CNSR	- Comet Nucleus Sample Return
COP	- Coefficient of Performance
COOLANT	- Cryogenic On-Orbit Liquid Analytical Tool Computer Code
COLD-SAT	- Cryogenic On-Orbit Liquid Depot Storage, Acquisition, and Transfer Satellite
CRES	- Corrosion Resistant Steel
CSF	- Customer Servicing Facility
DAK	- Double Aluminized Kapton
DB	- Database
DDT & E	- Design, Development, Test & Evaluation
DOD	- Department of Defense
DXS	- Diffuse X-Ray Spectrometer
ELV	- Expendable Launch Vehicle
EMLV	- Expendable Medium Launch Vehicle
EMM	- Evolutionary Mission Model
ET	- External Tank
EVA	- Extra Vehicular Activity

LIST OF ACRONYMS (continued)

FY	- Fiscal Year
FBB	- Fly Back Booster
FTS	- Flight Telerobotic Servicer
GBOTV	- Ground-Based Orbital Transfer Vehicle
GC	- Ground Conditioning
GD	- General Dynamics
GDSS	- General Dynamics Space Systems Division
GDNVF	- General Dynamics No-Vent Fill Computer Code
GH ₂	- Gaseous Hydrogen
GO ₂	- Gaseous Oxygen
GRO	- Gamma Ray Observatory
GSE	- Ground Support Equipment
GSFC	- Goddard Space Flight Center
HLLV	- Heavy Lift Launch Vehicle
I/F	- Interface
IOC	- Initial Operating Capability
IPF	- Integrated Processing Facility
IVA	- Inter-Vehicular Activity
JSC	- Johnson Space Center
LAD	- Liquid Acquisition Device
LAMAR	- Large Area Modular Array
LaRC	- Langley Research Center
LCC	- Life Cycle Cost
LDEF	- Long-Duration Exposure Facility
LDR	- Large Deployable Reflector
LEO	- Low Earth Orbit
LeRC	- Lewis Research Center
LHe	- Liquid Helium
LHSF	- Liquid Helium Servicing Facility
LH ₂	- Liquid Hydrogen
LL	- Lunar Landers

LIST OF ACRONYMS (continued)

LLO	- Low Lunar Orbit
LLOX	- Lunar Liquid Oxygen
LMO	- Low Mars Orbit
LN2	- Liquid Nitrogen
LO2	- Liquid Oxygen
LTCSF	- Long Term Cryogenic Storage Facility
MA	- Molecular Absorption
MAO	- Mars Aeronomy Orbiter
MLI	- Multilayer Insulation
MLV	- Medium Launch Vehicle
MMU	- Manned Maneuvering Unit
MRMS	- Mobile Remote Manipulator System
MSC	- Mobile Servicing Center
MSFC	- Marshall Space Flight Center
MSP	- Mars Surface Probe
MSR	- Mars Sample Return
NEAR	- Near-Earth Asteroid Rendezvous
NH3	- Ammonia
NMi	- Nautical Miles
NPSP	- Net Positive Suction Pressure
NSTS	- National Space Transportation System
OMV	- Orbital Maneuvering Vehicle
ORU	- Orbital Replacement Units
ORP	- Orbital Refueling Platform
OTSF	- Orbital Transfer & Staging Facility
OTV	- Orbital Transfer Vehicle
PDR	- Preliminary Design Review
PHA	- Preliminary Hazards Analysis
P-O	- Para-Ortho Hydrogen
PODS	- Passive Orbital Disconnect Strut
POP	- Polar Orbiting Platform

LIST OF ACRONYMS (continued)

PPO	- Polyphenylene Oxide
PRSTHRM	- Pressurization Thermodynamics Computer Code
RCS	- Reaction Control System
RF	- Radio Frequency
RMS	- Remote Manipulator System
R ³	- Rotary Reciprocating Refrigerator
RS	- Refrigeration Shield
SBAR	- Space Based Antenna Range
SBOTV	- Space Based Orbital Transfer Vehicle
SD-HLLV	- Shuttle Derived Heavy Lift Launch Vehicle
SDV	- Shuttle Derived Vehicle
SFHT	- Superfluid Helium Tanker
SF/P	- Saturn Flyby/Probe
SHIELD	- VCS/MLI/P-O Converter System Computer Code
SIRTF	- Space Infrared Telescope Facility
SO	- Saturn Orbiter
SSEC	- Solar System Exploration Committee
SSP	- Space Station Platform
3S	- Space Station Spartan
STAS	- Space Transportation Architecture System
STO/PIG	- Solar Terrestrial Observatory/Plasma Instrument Group
STO/SIG	- Solar Terrestrial Observatory/Solar Instrument Group
STS	- Space Transportation System
STV	- Space Transfer Vehicle
SUMIT	- Station User Mission Information Tracking
TBD	- To Be Determined
TD	- Tank Delivery
TDRSS	- Tracking and Data Relay Satellite System
TM	- Thermomechanical
T-S	- Temperature-Entropy
TVS	- Thermodynamic Vent System

LIST OF ACRONYMS (continued)

US	- United States
VAP	- Venus Atmospheric Probe
VCS	- Vapor Cooled Shield
V-M	- Vuilleumier
WBS	- Work Breakdown Structure
XGP	- Experimental Geo Platform

ADDITIONAL TERMS:

Code M	- NASA Office of Space Flight
Code Z	- NASA Office of Exploration
delta V	- A term within the discipline of orbital mechanics, usually in feet/second, relates to the energy required to place an object into a particular orbit
Hook	- A capability within a software architecture system to accommodate growth
Scar	- A capability within a preliminary hardware design to accommodate growth

1

INTRODUCTION

The Phase I Space Station, known as Freedom, is regarded as an essential element of NASA's continuing effort to ensure America's future in space. The station will play a key role in support of human exploration of the solar system. The station will also be an orbiting research laboratory for; 1) the conduct of science, 2) the development of technology, and 3) the stimulation of commercial space enterprises. Freedom is intended to be a permanently manned orbital facility, operating continuously for 30 years. The Space Station Freedom will be designed to evolve with time as needs and objectives change, to provide greater capability for ambitious missions and objectives. As new requirements and technologies emerge, Freedom will change to accommodate them. Specific areas include; available electrical power, the number of pressurized modules, experimental and cryogenic propellant storage/management capacity, and the number of attached external payloads. The evolution of the station is also viewed as a key element for Mars, lunar, and other exploration missions (Reference 1-1).

The Phase II or evolutionary Space Station may be used for a variety of purposes in support of NASA's Lunar, LEO, Mars and other space exploration missions. One of the most critical issues involves the storage, handling, and thermal/fluid management of the various fluids required at the station. Cryogenic propellants comprise the majority of the fluid requirements, and portions of this study were based on propellant storage system concepts developed under NASA-MSFC's Long Term Cryogenic Storage Facility System Study (References 1-2 through 1-5).

The primary purpose of this study was to define fluid storage and handling strategies/requirements for various specific mission case studies and their associated design impacts on the Space Station. Study objectives were accomplished by the following five tasks: (1) an inventory of all fluids expected to be associated with the Space Station during its initial and evolutionary phases, (2) identification of fluid management requirements such as storage, supply, transfer, handling, thermal, and safety issues, (3) development of several fluid management strategies and concepts for fluids accommodation to minimize "scarring" of the Space Station and its operations, and (4) identification of impacts to the Space Station design and operation systems and subsystems identified in Task 3 and the resulting design features to be included in the Space Station Phase I design to allow future fluid requirements, and (5), performing the required supporting activities; periodic progress and financial

reporting, status reviews, and coordination meetings.

Within the framework of the five Tasks outlined above, the restructuring of study objectives occurred interactively following Evolutionary Space Station working meetings, as requested by NASA-LeRC, to allow the maximum benefit of study results to NASA's overall Evolutionary Space Station program. These working meetings were hosted by NASA-LaRC to encourage the transfer of relevant information between NASA center contractors, and maintain uniformity with respect to NASA's overall program goals.

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FLUID REQUIREMENTS AT THE IOC/GROWTH SPACE STATION

This section describes the fluid requirements for the baseline and growth Space Station to support various functions and missions. These include supporting attached and free flying experimental payloads, OMV, STV, Planetary Initiative (described in Reference 2-1) and Code Z (Mars, Lunar, and other exploration) missions. The Code Z missions used for this study were based on Reference 2-2, and were four in number; 1) a human expedition to Phobos (Case study 1), 2) a human expedition to Mars (Case study 2), 3) the establishing of Lunar Observatories (Case study 3), and 4) using the Moon as a Lunar Outpost to early Mars Evolution (Case study 4). Reference 2-2 contains a detailed description of the Code Z mission models. The Space Station Fluid Requirements/Inventory data sheet (Table 2-1) shows a summary of the fluid requirements including the fluid type, phase, quantity, storage and delivery concept. The following sections will focus on the particular fluid support requirements for the individual missions.

2.1 EXPERIMENTAL PAYLOAD FLUID REQUIREMENTS

Some of the experimental payloads that are planned for the Space Station will require fluid replenishment. The servicing requirements for these payloads have been identified in several references including the Space Station Servicing Data Book generated by the BDM Corporation for the Office of Space Science and Applications (Reference 2-3). This data book is the most comprehensive of the fluid requirements sources. The SUMIT Database (DB), which is intended to collect all the Space Station user information into one DB that will be accessible to all "cleared users" via modem and personal computer, was not available at the time of the experimental fluid requirements identification. Also, the Evolution Mission Model (by McDonnell Douglas) DB has very little fluids information regarding experimental payloads. Therefore, a baseline of the experimental payload fluid requirements was established primarily based upon the BDM data books.

This baseline was used to facilitate the investigation of fluid management operational, safety and design concerns. Table 2-2 summarizes the baselined experimental payload fluid servicing requirements. This table shows the payload and its servicing interval, fluid type, quantity and servicing scenario. Although the actual experiment manifest for the Space Station has not been established,

the payloads identified in the baseline provided a representative assortment of servicing requirements that was used to examine fluid management issues such as storage, supply, transfer, handling, thermal and safety.

Figure 2-1 graphically summarizes the individual fluid types and amounts needed during each year to support the US experimental payloads. It is apparent from this Figure that liquid helium and hydrazine will be in the greatest demand. Table 2-3 presents a timephased look at the individual experimental fluid inventory requirements for Space Station users including US and international experimental payloads. The international experimental payload fluid requirements are assumed to be 30% of the US. This table also shows the total fluids needed per year and develops a fluids carrier schedule based upon the fluid carrier designs discussed in Section 3. The schedule has been arranged to include an appropriate number of resupply launches. Figure 2-2 graphically presents the number and type of fluids carriers needed during each year to support both US and International fluid needs. The previously mentioned data support the experimental payloads only. These requirements are assumed to remain constant regardless of the OMV, STV and Code Z missions selection.

The attached payloads primarily use rare gases for their sensors and instruments. The ASTROMAG, however, primarily uses superfluid helium for magnet cooling.

The free-flying experimental payloads require hydrazine for propulsion, nitrogen for attitude control, and also liquid helium for sensor/instrument cooling.

The greatest demands are for hydrazine and helium, which comprise 49 and 37% of the fluid needs, respectively.

The delivery schedule indicates that more liquid nitrogen is being delivered than is required. This was done to more efficiently utilize the fluid carriers, and also to provide additional nitrogen for unforeseen users (nitrogen is one of the most commonly used laboratory gases for purging and cleaning of environments).

2.2 OMV PROPELLANT REQUIREMENTS

Even though the OMV is currently designed to be serviced from the Shuttle, basing an OMV at the Space Station is practical, efficient and "assumed" by a number of studies to exist. Therefore, a Space Station based OMV concept was assumed for the purposes of this study. The OMV requires hydrazine, bi-prop, and nitrogen. Free-flying experiments also require hydrazine, which also makes

Table 2-1. Sources for Space Station Fluid Inventory

SOURCES FOR SPACE STATION FLUID REQUIREMENTS					
SOURCE	DESCRIPTION	TYPE	PHASE	STORAGE CONCEPT	DELIVERY
Ref 2-1 pg 2-16	Station Users (Misc)	Nitrogen	Liquid	Fluid Logistics Carrier	Shuttle/ELV
Ref 2-3		Helium	Liquid	Fluid Logistics Carrier	Shuttle/ELV
		Helium	Gas	Fluid Logistics Carrier	Shuttle/ELV
		Argon	Gas	Fluid Logistics Carrier	Shuttle/ELV
		Oxygen	Liquid	Fluid Logistics Carrier	Shuttle/ELV
Ref 2-1 pg 5-18	OMV	Bi-Prop	Liquid	OMV Prop Module	Shuttle
		Hydrazine	Liquid	Unspecified	Shuttle
		Nitrogen	Gas	Unspecified	Shuttle
Ref 2-3	AstroMag	Helium	Liquid	Cryostat on Experiment	Shuttle
Ref 1-4 pg 2-4/5	STV (Rev 8 w/o Planetary)	Hydrogen	Liquid	LTCSF	HLLV
		Oxygen	Liquid	LTCSF	HLLV
Ref 2-1 pg 5-15	Planetary Initiative				
	Mars Sample Return	O2/H2 6:1	Liquid	Unspecified	HLLV
	Venus Atm Probe	O2/H2 6:1	Liquid	Unspecified	HLLV
	Mars Aeronomy Orb	O2/H2 6:1	Liquid	Unspecified	HLLV
	Lunar Landers	O2/H2 6:1	Liquid	Unspecified	HLLV
	Comet Atom. Samp Ret	O2/H2 6:1	Liquid	Unspecified	HLLV
	Mars Surface Probe	O2/H2 6:1	Liquid	Unspecified	HLLV
	Saturn Orbiter	O2/H2 6:1	Liquid	Unspecified	HLLV
	Saturn Flyby/Probe	O2/H2 6:1	Liquid	Unspecified	HLLV
	Comet Nuc Samp Ret	O2/H2 6:1	Liquid	Unspecified	HLLV
	Near Earth Astd Rend	O2/H2 6:1	Liquid	Unspecified	HLLV
Ref 2-2 pg 2-114	LUNAR OBSERVATORIES	O2/H2 7:1	Liquid	Unspecified	HLLV
Ref 2-2 pg 2-8	MANNED PHOBOS	O2/H2 7:1	Liquid	Unspecified	HLLV
	Storables	Bi-Prop	Liquid	Unspecified	
Ref 2-2 pg 2-53	MARS EXPEDITION	O2/H2 7:1	Liquid	Unspecified	HLLV
	Storables	Bi-Prop	Liquid	Unspecified	
Ref 2-2 pg 2-179a	LUNAR BASE TO MARS	Hydrogen	Liquid	Unspecified	HLLV
		Oxygen	Liquid	Unspecified	HLLV
		Argon	Liquid	Unspecified	HLLV
	(May use SS)	Hydrogen	Liquid	Unspecified	HLLV
		Oxygen	Liquid	Unspecified	HLLV

Table 2-2. Space Station Experimental Payload Servicing Summary.

SS SERVICING DATA BOOK FOR OSSA ATTACHED PAYLOADS					(BDM - MARCH 1989)			
Payload Title	Launch	First Serv.	Serv. Interval	Life	Fluid Type	Mass (kgs)	Volume (m3)	Servicing Notes
ATTACHED								
ASTROMAG	1996		1996 1.5 - 2 YRS	10 YRS	LIQ HELIUM	580	4	dewar EVA/IVA hookup at payload
DXS	Unman-SpacSta	TBD	TBD	THRU POST PHASE 1	GAS P-10	100	TBD	gas bottle changeout via EVA/IVA (MSC)
LAMAR	TBD	LAUNCH+3	3 YRS	TBD	ARGON METHANE XENON	90% 10% 90%	TBD	gas module changeout via EVA/IVA
STO/SIG	1995	1995	QUARTERLY	4 YRS	METHANE	10%	TBD	
STO/PIG	1994	1994	QUARTERLY	4 YRS	NITROGEN	0.4	9	gas bottle changeout via EVA/IVA (MSC)
STO/SS	1994	1994	QUARTERLY	4 YRS	ARGON/XENON	25/1	.005/.010	gas bottle changeout via EVA/IVA (MSC)
					NITROGEN	0.4	0.01	gas bottle changeout via EVA/IVA (MSC)
FREE FLYERS								
AXAF	1995	1998	36 MONTHS	15 YRS	LIQHELIUM	29	TBD	OMV r/d, EVA/IVA fluid transfer while brethed
GRO	1990	1994	4 YRS	4YRS/8YRS	HYDRAZINE	1024	1	OMV r/d, EVA/IVA fluid transfer while brethed
LDR	2000	2000	2 YRS	15 YRS	LIQHELIUM	800	5000	in-situ servicing via OMV/FTS
	2001							
SBAR	1997	1997	6 MONTHS	INDEFINITE	HYDRAZINE	380		OMV r/d, EVA/IVA fluid transfer while brethed
					COLD GAS	TBD		
SIRTF	1996	1998	18 MONTHS	10 YRS	LIQHELIUM	1740	12	OMV r/d, EVA/IVA fluid transfer while brethed
3S	1996	1996	1996-98 2/YR	TBD-10YR	HYDRAZINE	380		OMV r/d, EVA/IVA fluid transfer while brethed
					COLD GAS	TBD		
STO/POP	1994	1995	1 YR	4 YRS	TBD			in-situ servicing via OMV/FTS
	1999	2000		4-6 YRS	TBD			
					ARGON	0.25	0.005	
					XENON	1.9	0.01	
					NITROGEN	4.5	0.11	
XGP	1998	1998	3 YRS	20 YRS	HYDRAZINE	1000	1	in-situ servicing via STV/OMV/FTS
OMV r/d= Orbital Maneuvering Vehicle retrieval and deployment								
FTS= Flight Telerobotic Servicer								
MSC= Mobile Servicing Center								

Table 2-3. Space Station Experimental Fluid Requirements

Payload Title Fluid Type 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 TOTAL

US EXPERIMENTAL PAYLOAD FLUID REQUIREMENTS BY MASS (kgs)

ATTACHED PAYLOADS																
ASTROMAG	LHe	580	580	580	580	580	580	580	580	580	580	580	580	580	580	3480
	Rare Gas	100	100	100	100	100	100	100	100	100	100	100	100	100	100	600
DXS (guesses)	Argon		650		650		650		650		650		650		650	2600
	Methane		73		73		73		73		73		73		73	292
LAMAR	Xenon		650		650		650		650		650		650		650	2600
	Methane		73		73		73		73		73		73		73	292
STO/PIG	Xenon	8	8	8	8	8	8	8	8	8	8	8	8	8	8	32
	Argon	1	1	1	1	1	1	1	1	1	1	1	1	1	1	4
STOSIG	Nitrogen	2	2	2	2	2	2	2	2	2	2	2	2	2	2	8

FREE FLYER PAYLOADS

AXAF	LHe		30				30				30				30	150
GRO	Hydrazine	1024					1024									2048
LDR	LHe						800				800				800	4800
SBAR	Hydrazine		760	760	760	760	760	760	760	760	760	760	760	760	760	6080
	N2 (guess)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	160
SIRTF	LHe		1740		1740		1740		1740		1740		1740		1740	10440
3S	Hydrazine	760	760	760	760	760	760	760	760	760	760	760	760	760	760	11400
	N2 (guess)	30	30	30	30	30	30	30	30	30	30	30	30	30	30	450
XGP	Hydrazine		1000				1000				1000				1000	5000

US EXPERIMENTAL SPECIFIC FLUID REQUIREMENTS BY MASS (kgs)

LHe	580	0	2320	30	2320	2540	610	2540	830	2320	830	30	800	0	830	18870
Rare Gas	100	0	100	0	100	0	100	0	100	0	100	0	0	0	0	600
Argon	1	1	651	1	0	650	0	0	650	0	0	650	0	0	0	2604
Methane	0	0	73	73	0	73	73	0	73	73	0	73	73	0	0	584
Xenon	8	8	658	0	0	650	0	0	650	0	0	650	0	0	0	2632
Nitrogen	32	52	52	67	65	65	65	65	65	45	45	0	0	0	0	618
Hydrazine	1784	1520	2520	1900	2924	2900	1900	1900	2900	1140	1140	1000	0	1000	0	24528

US EXPERIMENTAL YEARLY FLUID REQUIREMENTS BY MASS (kgs)

2505	1581	5724	2729	5409	6228	3398	4505	6108	2738	3605	2523	753	800	1000	830	50436
------	------	------	------	------	------	------	------	------	------	------	------	-----	-----	------	-----	-------

US EXPERIMENTAL SPECIFIC FLUID REQUIREMENTS BY VOLUME (liters)

LHe	4525.6	0	18102	234.08	18102	19819	4759.7	19819	18102	6476.3	18102	6242.2	234.08	6242.2	0	6476.3	147238
Rare Gas	90	0	90	0	90	0	90	0	90	0	90	0	0	0	0	540.001	
Argon	256.88	0	256.88	0	256.88	0	256.88	0	256.88	0	256.88	0	0	0	0	1541.28	
Methane	0	0	474.64	474.64	0	474.64	474.64	0	474.64	474.64	0	474.64	474.64	0	0	3797.14	
Xenon	6.2578	6.2578	514.71	0	0	508.45	0	0	508.45	0	0	508.45	0	0	0	2058.83	
Nitrogen	39.95	64.919	83.645	81.149	81.149	81.149	81.149	81.149	81.149	56.18	56.18	0	0	0	0	771.536	
Hydrazine	1796.1	1530.3	2537.2	1912.9	2943.9	2919.7	1912.9	1912.9	2919.7	1147.8	1147.8	1006.8	0	1006.8	0	24694.9	

Table 2-3. Space Station Experimental Fluid Requirements (continued)

Fluid Type	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	TOTAL
RECOMMENDED US EXPERIMENTAL SPECIFIC FLUID DELIVERY BY VOLUME (liters)																	
LHe	10000	0	20000	0	20000	20000	0	20000	20000	0	20000	0	0	10000	0	10000	150000
Rare Gas	400	0	0	0	0	0	0	0	400	0	0	0	0	0	0	0	800
Argon	400	0	400	0	0	0	400	0	400	0	0	0	0	0	0	0	1600
Methane	0	0	800	400	0	400	400	0	400	800	0	400	400	0	0	0	4000
Xenon	400	0	0	400	0	0	400	0	0	400	0	0	800	0	0	0	2400
Nitrogen	6000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6000
Hydrazine	6000	0	0	6000	0	6000	0	0	6000	0	0	0	0	0	6000	0	30000
INTERNATIONAL SPECIFIC FLUID REQUIREMENTS BY MASS (kgs) (see note at bottom)																	
LHe	174	0	696	9	696	762	183	762	696	249	696	240	9	240	0	249	5661
Rare Gas	30	0	30	0	30	0	30	0	30	0	30	0	0	0	0	0	180
Argon	0.3	0.3	195.3	0.3	0	195	0	195	0	195	0	195	0	0	0	0	781.2
Methane	0	0	21.9	21.9	0	21.9	21.9	0	21.9	21.9	0	21.9	21.9	0	0	0	175.2
Xenon	2.4	2.4	197.4	0	0	195	0	195	0	195	0	195	0	0	0	0	789.6
Nitrogen	9.6	15.6	15.6	20.1	19.5	19.5	19.5	19.5	19.5	13.5	13.5	0	0	0	0	0	185.4
Hydrazine	535.2	456	756	570	877.2	870	570	570	870	342	342	300	0	0	300	0	7358.4
INTERNATIONAL SPECIFIC FLUID REQUIREMENTS BY VOLUME (liters) (see note at bottom)																	
LHe	1357.7	0	5430.7	70.225	5430.7	5945.7	1427.9	5945.7	5430.7	1942.9	5430.7	1872.7	70.225	1872.7	0	1942.9	44171.3
Rare Gas	27	0	27	0	27	0	27	0	27	0	27	0	0	0	0	0	162
Argon	0.7706	0.7706	501.69	0.7706	0	500.92	0	500.92	0	500.92	0	500.92	0	0	0	0	2006.75
Methane	0	0	142.39	142.39	0	142.39	142.39	0	142.39	142.39	0	142.39	142.39	0	0	0	1139.14
Xenon	1.8774	1.8774	154.41	0	0	152.53	0	152.53	0	152.53	0	152.53	0	0	0	0	617.649
Nitrogen	11.985	19.476	19.476	25.094	24.345	24.345	24.345	24.345	24.345	16.854	16.854	0	0	0	0	0	231.461
Hydrazine	538.84	459.1	761.15	573.88	883.17	875.92	573.88	573.88	875.92	344.33	344.33	302.04	0	0	302.04	0	7408.48
US & INTERNATIONAL EXPERIMENTAL SPECIFIC FLUID REQUIREMENTS BY MASS (kgs)																	
LHe	754	0	3016	39	3016	3302	793	3302	3016	1079	3016	1040	39	1040	0	1079	24531
Rare Gas	130	0	130	0	130	0	130	0	130	0	130	0	0	0	0	0	780
Argon	130	0	130	0	130	0	130	0	130	0	130	0	0	0	0	0	780
Methane	0	0	94.9	94.9	0	94.9	94.9	0	94.9	94.9	0	94.9	94.9	0	0	0	759.2
Xenon	10.4	10.4	10.4	855.4	0	845	0	845	0	845	0	845	0	0	0	0	3421.6
Nitrogen	41.6	67.6	67.6	87.1	84.5	84.5	84.5	84.5	84.5	58.5	58.5	0	0	0	0	0	803.4
Hydrazine	2319.2	1976	3276	2470	3801.2	3770	2470	2470	3770	1482	1482	1300	0	0	1300	0	31886.4
US & INTERNATIONAL EXPERIMENTAL YEARLY FLUID REQUIREMENTS BY MASS (kgs)																	
3344	1986	6657	3459	7077	7167	4463	5772	7141	3501	4758	2435	978.9	1040	1300	1079	62158.2	
US & INTERNATIONAL EXPERIMENTAL SPECIFIC FLUID REQUIREMENTS BY VOLUME (liters)																	
LHe	5883.3	0	23533	304.31	23533	25765	6187.6	25765	23533	8419.2	23533	8114.9	304.31	8114.9	0	8419.2	191409
Rare Gas	117	0	117	0	117	0	117	0	117	0	117	0	0	0	0	0	702.001
Argon	333.94	0	333.94	0	333.94	0	333.94	0	333.94	0	333.94	0	0	0	0	0	2003.67
Methane	0	0	617.04	617.04	0	617.04	617.04	0	617.04	617.04	0	617.04	617.04	0	0	0	4936.28
Xenon	8.1352	8.1352	669.12	0	0	660.98	0	660.98	0	660.98	0	660.98	0	0	0	0	2676.48
Nitrogen	51.935	84.395	84.395	108.74	105.49	105.49	105.49	105.49	105.49	73.034	73.034	0	0	0	0	0	1003
Hydrazine	2335	1989.4	3298.3	2486.8	3827.1	3795.7	2486.8	2486.8	3795.7	1492.1	1492.1	1308.8	0	0	1308.8	0	32103.4

Table 2-3. Space Station Experimental Fluid Requirements (continued)

Fluid Type	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	TOTAL
RECOMMENDED US AND INTERNATIONAL EXPERIMENTAL SPECIFIC FLUID DELIVERY BY VOLUME (liters)																	
LHe	10000	0	20000	0	30000	20000	10000	30000	20000	10000	20000	10000	0	10000	0	10000	200000
Rare Gas	400	0	0	0	0	0	400	0	0	0	0	0	0	0	0	0	800
Argon	400	0	400	0	400	0	400	0	400	0	400	0	0	0	0	0	2400
Methane	0	0	800	800	0	400	800	0	400	800	0	400	800	0	0	0	5200
Xenon	400	0	400	0	400	0	800	0	400	800	0	400	0	0	0	0	2800
Nitrogen	6000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6000
Hydrazine	6000	6000	0	0	6000	0	6000	0	6000	0	6000	0	0	0	0	0	36000
US & INTERNATIONAL EXPERIMENTAL FLUID CARRIER REQUIREMENTS (fluids measured in liters)																	
LHe	10000	0	20000	0	30000	20000	10000	30000	20000	10000	20000	10000	0	10000	0	10000	200000
# of carriers	1	0	2	0	3	2	1	3	2	1	2	1	0	1	0	1	20
HYDRAZINE CARRIER																	
Hydrazine	6000	6000	0	0	6000	0	6000	0	6000	0	6000	0	0	0	0	0	36000
# of carriers	1	1	0	0	1	0	1	0	1	0	1	0	0	0	0	0	6
MISC. FLUIDS CARRIER																	
RECOMMENDED US, INT'L EXPERIMENTAL MISC. FLUID DELIVERY BY VOLUME (OPTIMIZED FOR MINIMUM LAUNCHES)																	
Rare Gas	400	0	0	400	0	0	0	0	0	0	0	0	0	0	0	0	800
Argon	800	0	0	800	0	0	800	0	0	0	0	0	0	0	0	0	2400
Methane	1600	0	0	1200	0	0	1200	0	0	0	0	1200	0	0	0	0	5200
Xenon	400	0	0	800	0	0	1200	0	0	0	0	400	0	0	0	0	2800
Nitrogen	6000	0	0	6000	0	0	6000	0	0	0	0	6000	0	0	0	0	24000
# of carriers	1	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	4
TOTAL YEARLY FLUIDS CARRIERS																	
	3	1	2	1	4	2	3	3	3	1	3	2	0	1	0	1	30

NOTE: The international experimental fluid requirements are assumed to be 30% of the US specifications.

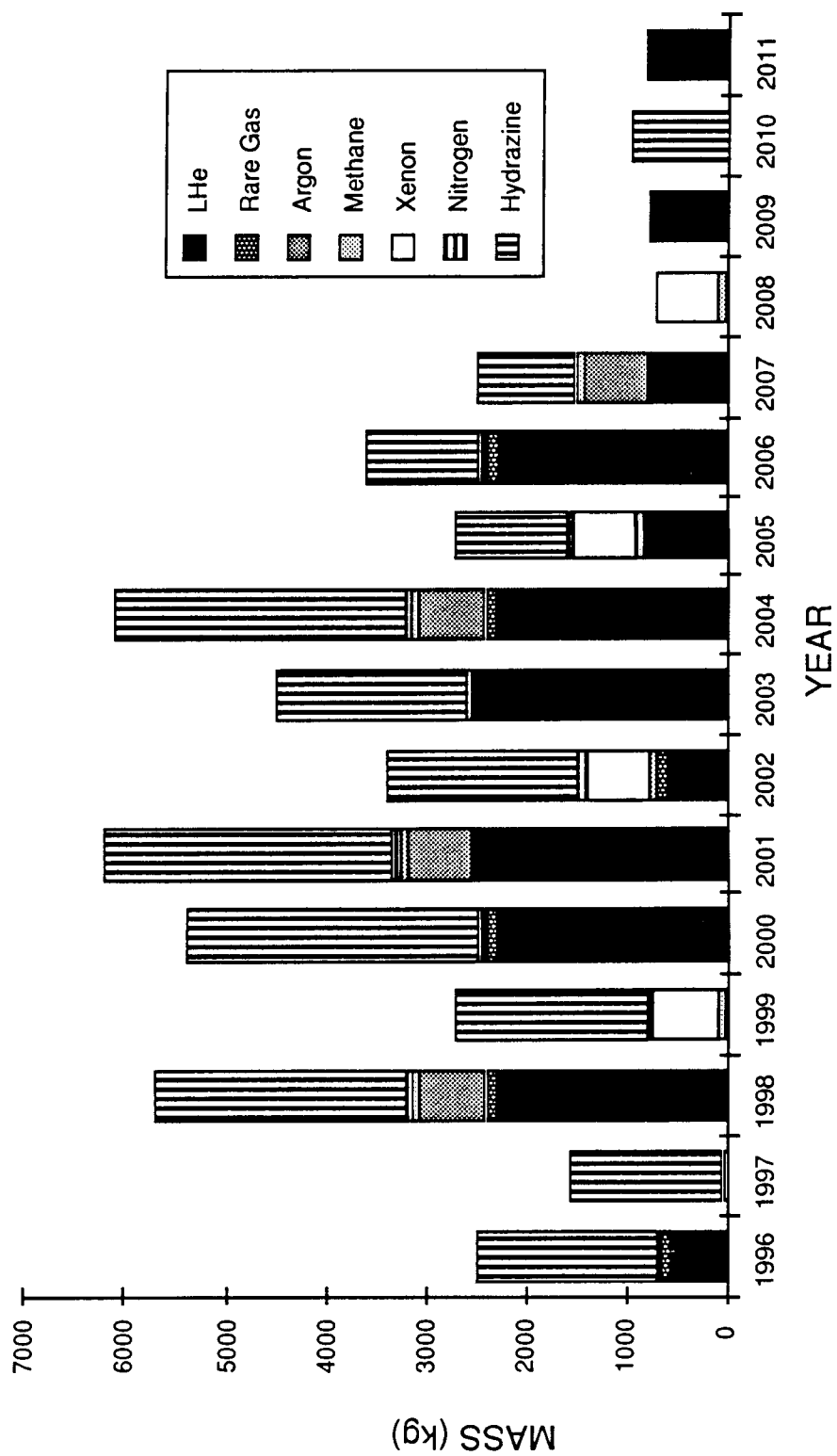


Figure 2-1. Space Station US Experimental Payload Fluid Requirements

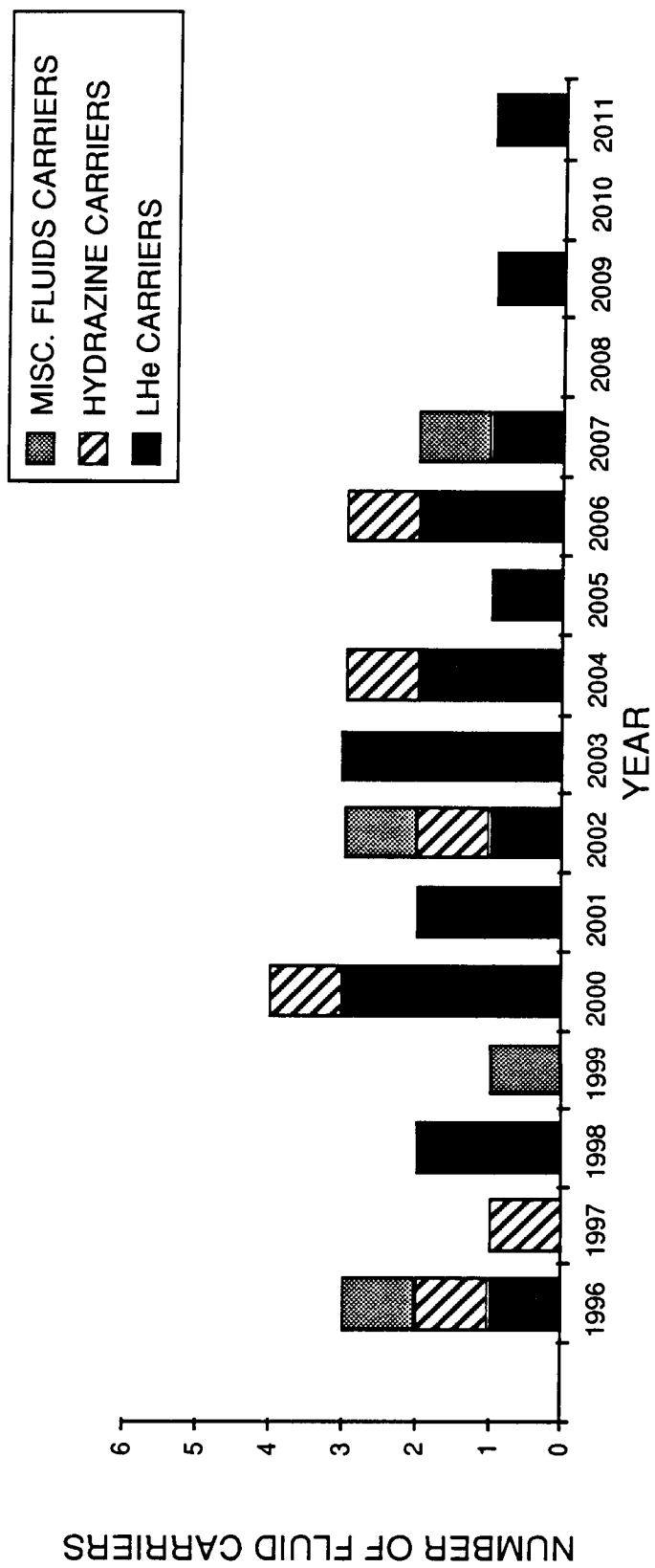


Figure 2-2. US and International Fluids Carrier Requirements

hydrazine storage at the SS desirable.

Table 2-4 (Tables 2-5, 2-6 and 2-7 contain the same OMV propellant data) shows the amount of OMV propellants required to support the flights identified. Although the number of flights (estimates from Reference 2-2) do not extend beyond 2004 and are probably fewer than would be realized, they provide a basis for the study of the impact upon Space Station fluid management requirements. The number of OMV flights will probably be significantly greater when Station operations, logistics using expendable launch vehicles, satellite servicing and proximity transportation is accounted for. Data for the fluid requirements of these types of missions is not currently available. Figure 2-3 graphically illustrates the OMV fluid requirements.

2.3 SPACE TRANSFER VEHICLE PROPELLANT REQUIREMENTS

The STV will be used to retrieve and deliver payloads from the Space Station to higher energy orbits (e.g. geosynchronous). The propellant requirements for these missions are based upon NASA's Mission Model for the OTV (Revision 8) with all Lunar and planetary missions removed. The STV reference configuration is the "MSFC synthesized" version (see Figure 2-4). The propellants are liquid oxygen and hydrogen, burned at a 6:1 mass ratio.

The STV propellant requirements are shown in Table 2-4 (Tables 2-5, 2-6 and 2-7 contain the same STV data). Although the STV model used in this study is larger than the current STV flight estimates, the addition of DOD missions and Mission-to-Planet-Earth geosynchronous fluid requirements will result in an increase in the STV propellant requirements.

Accounting for the Mission-to-Planet-Earth Polar Orbiting Platform (POP) servicing would require extra propellant storage at the Space Station. However, servicing from the Space Station is not currently planned because polar orbits are most efficiently accessed from the ground (minimum delta V and propellant requirements). Therefore POP servicing from the Space Station was not considered in this study. Figure 2-5 graphically represents the STV propellant requirements.

2.4 PLANETARY INITIATIVES

This mission model was taken from Reference 2-1 and is the augmented mission program as recommended by the Solar System Exploration Committee (SSEC) of the NASA Advisory Council. The Planetary Initiative missions are accomplished with the STV, and the propellant requirements are LO₂/LH₂. Any additional fluids associated with these missions are assumed to be part of the payload

(and not serviced/replenished at the SS). These propellant requirements are shown in Table 2-4 (Tables 2-5, 2-6 and 2-7 contain the same Planetary Initiative data) for the years of the individual missions launch and/or operation. The total propellant requirements for the STV Mission Model are more than an order of magnitude greater than the propellants required for the Planetary Initiatives. The Planetary Initiative fluid requirements are graphically presented in Figure 2-6.

2.5 CODE Z MISSION FLUID REQUIREMENTS

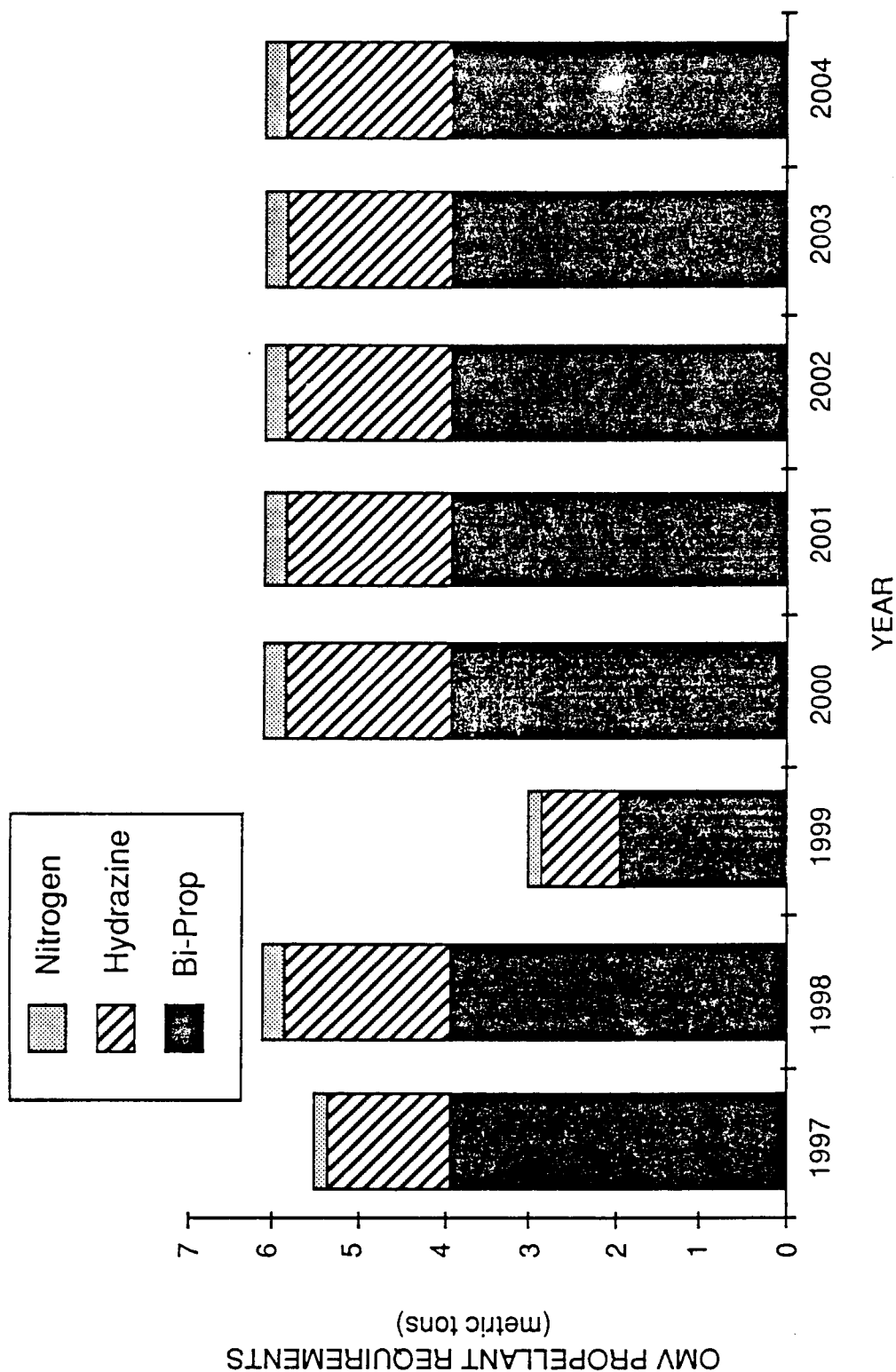
The Office of Exploration (Code Z) case studies are defined in Reference 2-2. This document identifies the propellant requirements for the Human Expedition to Phobos, Human Expeditions to Mars, Lunar Observatories and Lunar Outpost to Early Mars Evolution missions. The Space Station fluid support requirements are separated into four individual schedules, each one based upon a single Code Z mission, since it is very unlikely that two or more Code Z missions will be done concurrently.

An identical set of combined SS experiments, OMV, STV and Planetary Initiative fluid requirements are included with each of the Code Z mission models. The new 1989 Code Z missions with the upmass to LEO limit of 570 metric tons (mt) per year were not used in this analysis because of the lack of propellant requirements.

Figure 2-7 illustrates the relative propellant quantity and timephasing requirements of the individual Code Z missions. Although some of the fluid requirements for the Code Z missions are needed at locations other than LEO (i.e. Lunar vicinity) it is assumed that the fluids will "go through" the Space Station or a co-orbiting depot before reaching their final destination. It is clear from this comparison that Mars Expedition propellant requirements are the greatest of the Code Z mission propellant requirements.

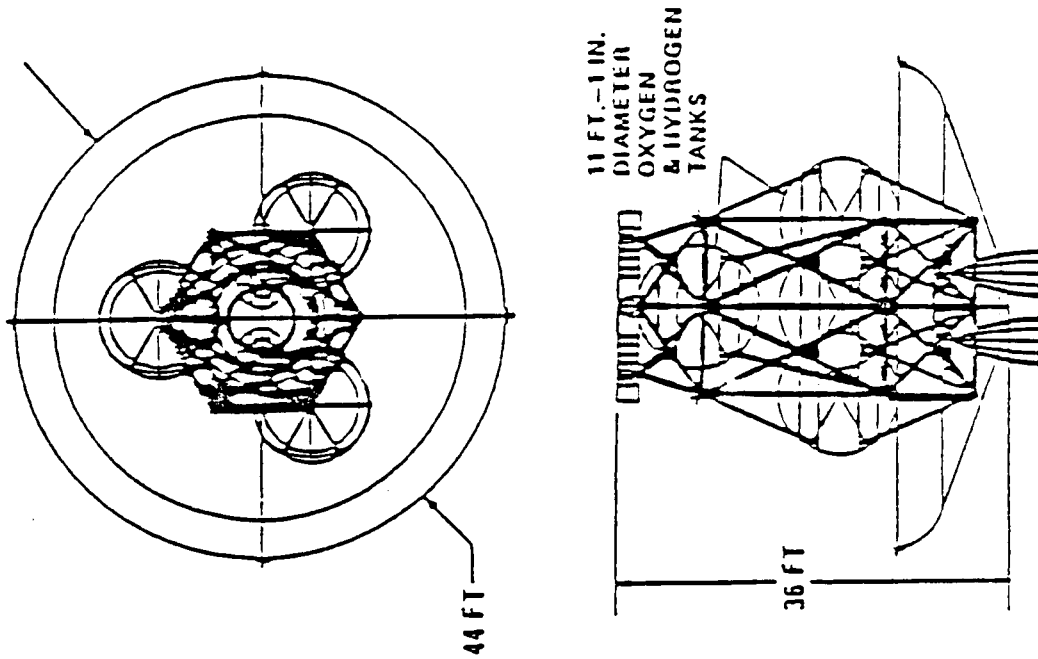
Due to the large quantities involved it is unlikely that any of the Code Z propellants will be stored at the Space Station (due to operations, safety, logistics, dynamics, and stationkeeping considerations), unless the primary purpose of the SS becomes that of a transportation node.

2.5.1 MANNED PHOBOS MISSION. The Manned Phobos Mission propellant requirements are defined in Table 2-4, and total approximately 1500 metric tons between the years 2000 and 2003. This mission has the earliest of the Code Z fluid requirements, and therefore the space infrastructure must be capable of supporting fluid storage, resupply and transfer by the year 2000/2001. However, the fluid requirements only run through the year 2003, and hence may not justify the development



NOTE: This estimate of OMV propellant requirements comes from the "Space Station Transportation Interfaces", NASA, JSC, August 1988.

Figure 2-3. Orbital Maneuvering Vehicle Propellant Requirements, 1997 to 2004



MISSION CAPABILITY	
• GEO CIRCULAR	31,890 LB
--- EXPENDABLE	20,000 LB
--- REUSABLE	60 HRS
• MAXIMUM DURATION	12,000 UP/2,000 DOWN
• GEO SERVICE STATION LOGISTICS	
STAGE DESCRIPTION	
• DRY WEIGHT	9,070 LB
• BURNOUT WEIGHT	10,460 LB
• USABLE MAIN PROPELLANT	58,540 LB
• STAGE IGNITION WEIGHT	69,000 LB
• AIRBORNE SUPPORT EQUIPMENT	TBD
PROPULSION	
• PROPELLANT TYPE	O ₂ /H ₂ (1 ATM)
• NO. MAIN ENGINE	2
• MIXTURE RATIO/ISP	6:1/485
• AVERAGE THRUST LEVEL	5,000 LB (PER ENG.)
• RCS PROPELLANT	N ₂ H ₄
AVIONICS	
• TYPE	3 STRING
• POWER	FUEL CELL (PROPELLANT GRADE REACTANTS)

Figure 2-4. Space Based STV Reference Configuration (NASA MSFC Synthesized Version).

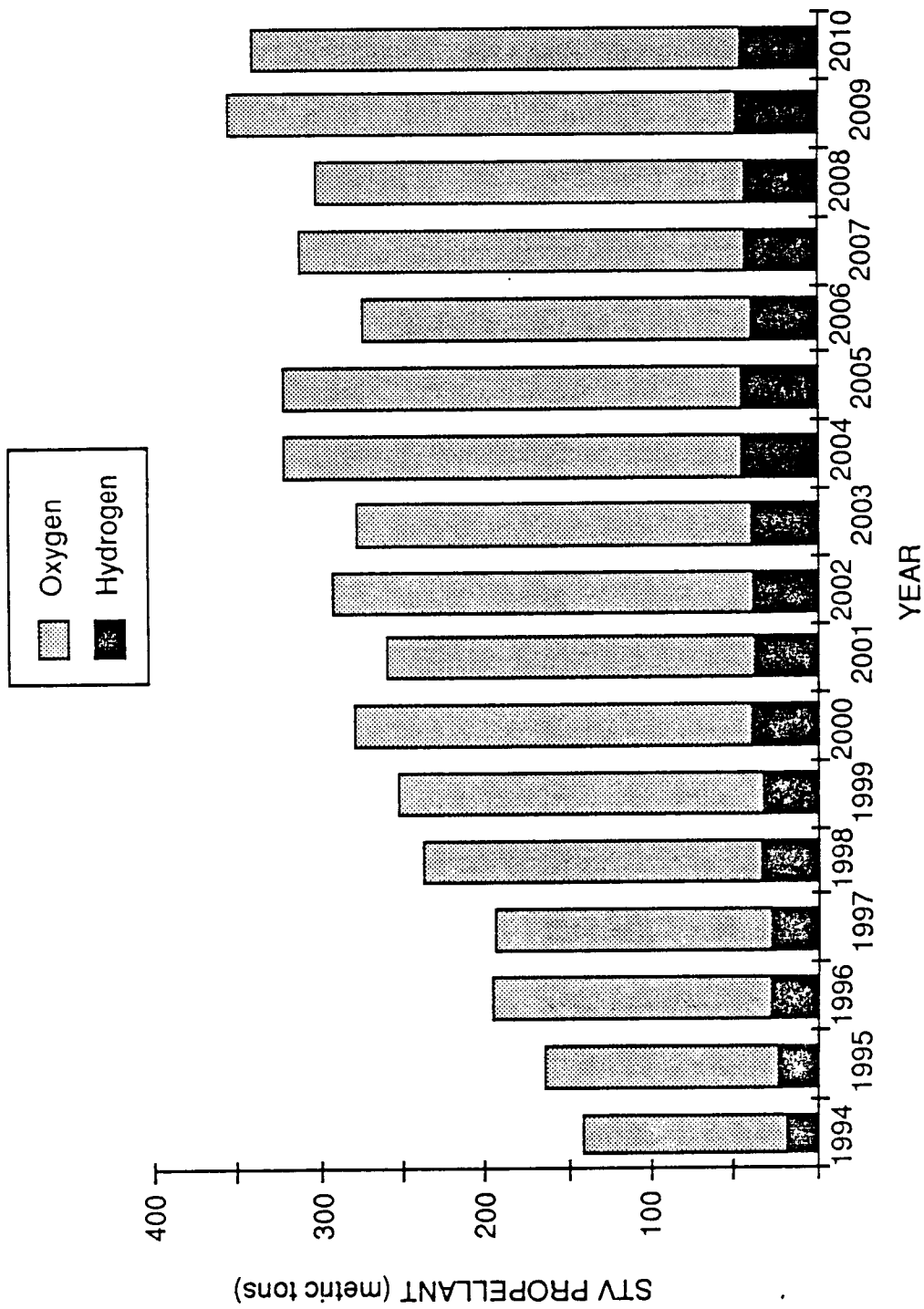
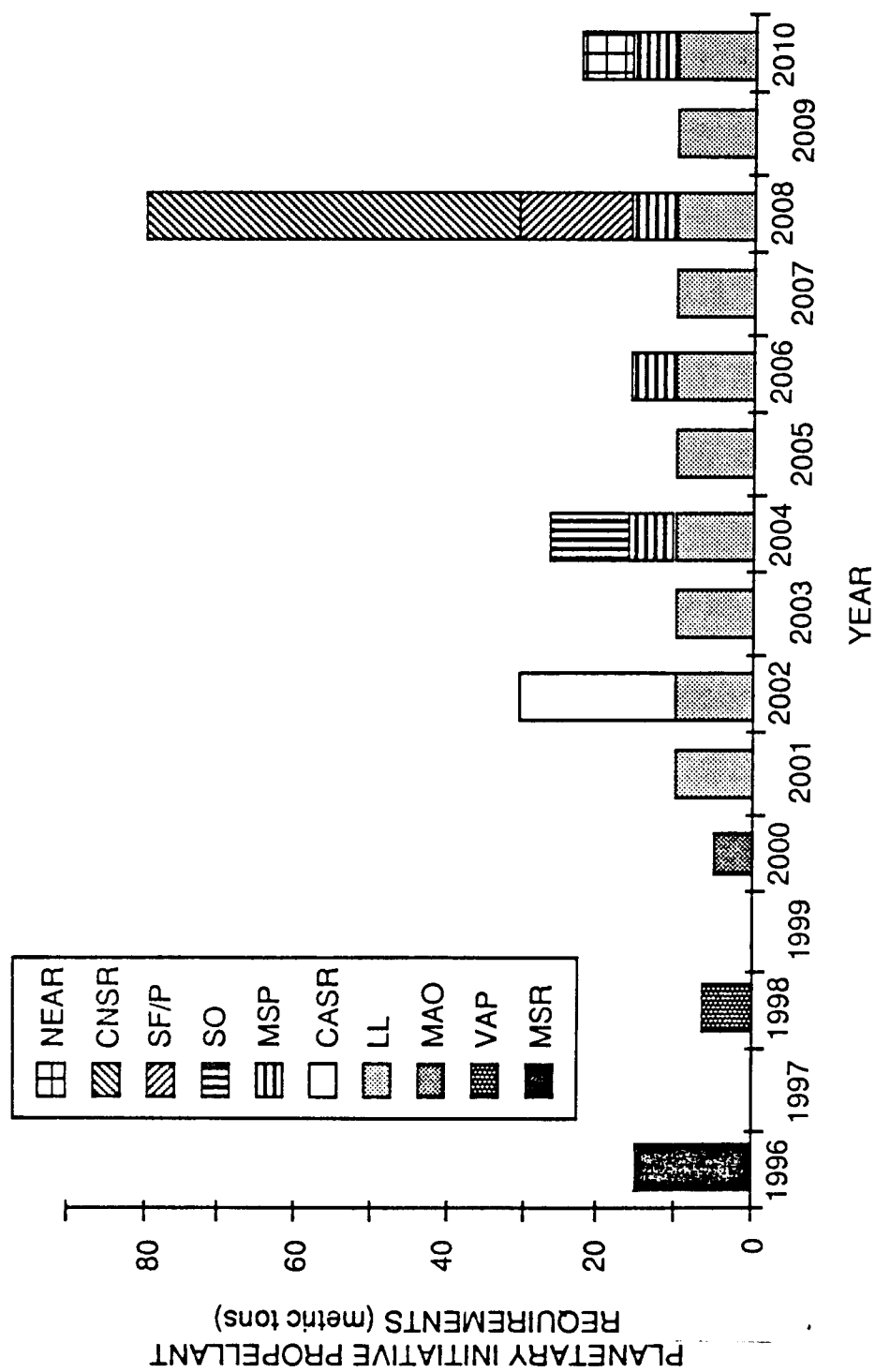


Figure 2-5. Space Transfer Vehicle (from OTV Revision 8 Mission Model) Propellant Requirements, 1994 to 2010



NOTE: This estimate of expendable STV propellant requirements comes from the "Space Station Transportation Interfaces", NASA, JSC, August 1988. It represents the augmented mission program recommended by the Solar System Exploration Committee of the NASA Advisory Council.

Figure 2-6. Planetary Initiative Propellant Requirements (expendable STV missions), 1996 to 2010

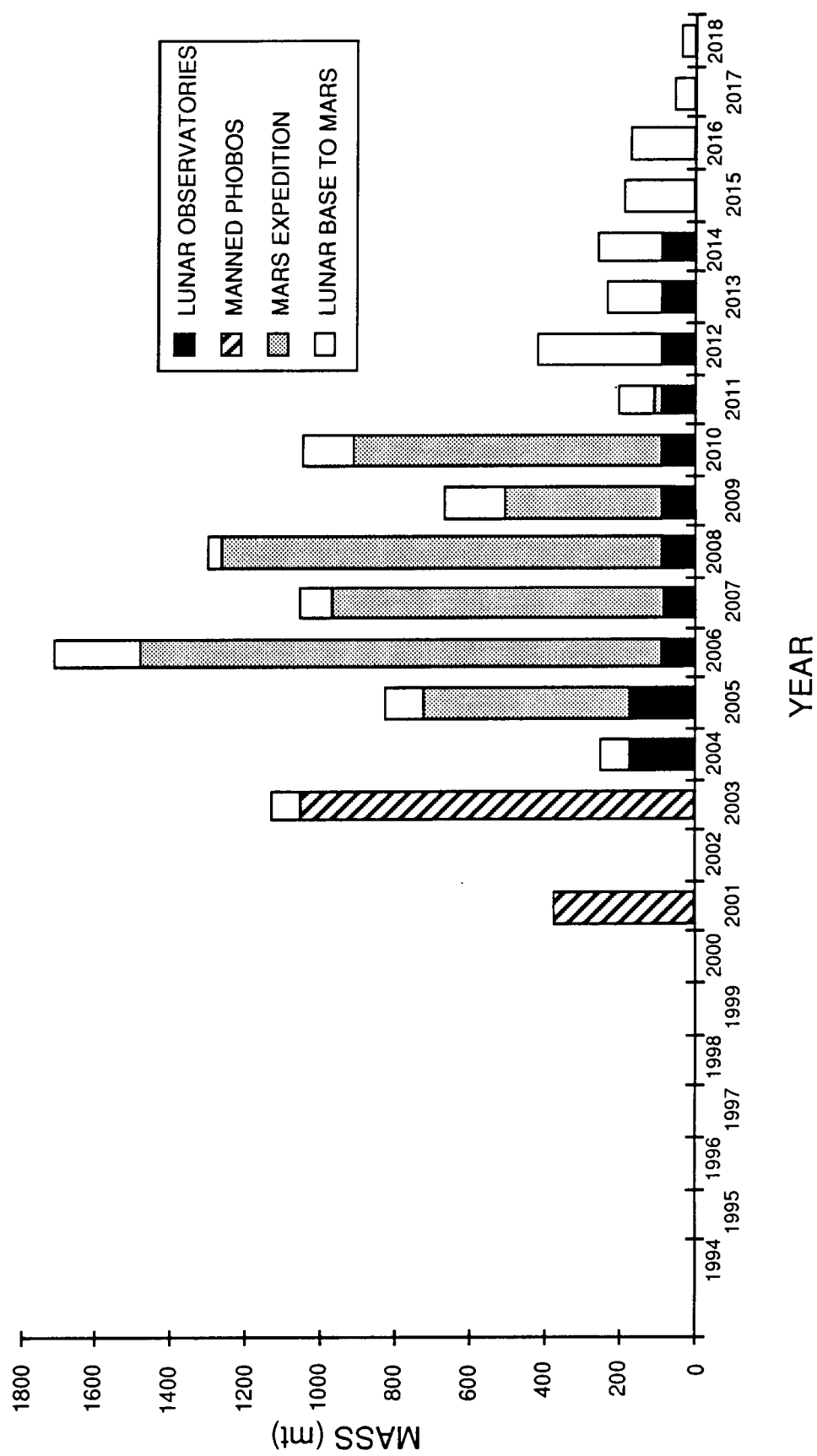


Figure 2-7. Code Z Mission Fluid Requirements, 2001 to 2018

Table 2-4. Comprehensive Space Station Fluid Requirements (Manned Phobos)

DESCRIPTION	1994		1995		1996		TIMEPHASED FLUID MASS REQUIREMENTS										2004		2005		2006	
	(mt)	(mt)	(mt)	(mt)	(mt)	(mt)	(mt)	(mt)	(mt)	(mt)	(mt)	(mt)	(mt)	(mt)	(mt)	(mt)	(mt)	(mt)				
US EXPERIMENTAL PAYLOAD FLUID REQUIREMENTS																						
	0	0	0	2.505	1.581	5.724	2.729	5.409	6.228	3.398	4.505	6.108	2.738	3.605								
OMV (FLIGHTS)	0	0	0		3	4	2	4	4	4	4	4										
Bi-Prop					4	4	2	4	4	4	4	4			4							
Hydrazine					1.5	2	1	2	2	2	2	2			4							
Nitrogen					0.2	0.3	0.2	0.3	0.3	0.3	0.3	0.3			2							
												0.3			0.3							
STV (Rev 8 w/o Planetary)	145	166	197	196	196	239	256	281	261	297	278	321	321									
Hydrogen	20.7	23.7	28.1	28.0	28.0	34.1	36.6	40.1	37.3	42.4	39.7	45.9	45.9			275						
Oxygen	124.3	142.3	168.9	168.0	168.0	204.9	219.4	240.9	223.7	254.6	238.3	275.1	275.1			39.3						
																235.7						
Planetary Initiative																						
MSR																						
VAP				16.1																		
MAO						7.2																
LL								5.9														
CASR									10.9	10.9	10.9	10.9	10.9			10.9						
MSP										21.64												
SO																6.7						
SF/P													6.7									
CNSR												11.3										
NEAR																						
MANNED PHOBOS																						
Storables									378			1068										
TOTALS	145	166	215.6	203.3	258.2	261.9	298.6	669.4	339.2	1384	362.3	334.6	296.2									

Table 2-4. Comprehensive Space Station Fluid Requirements (Manned Phobos) (continued)

DESCRIPTION	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	GRAND
	(ml)	(mt)	(ml)	(ml)	(ml)	(ml)	(ml)	(ml)	(ml)	(ml)	(ml)	(ml)	TOTALS
US EXPERIMENTAL PAYLOAD													
	2.523	0.753	0.8	1	0.83	0	0	0	0	0	0	0	50.436
OMV (FLIGHTS)													
Bi-Prop													29.0
Hydrazine													30.0
Nitrogen													14.5
													2.2
STV (Rev 8 w/o Planetary)													
	311	303	357	341									4545.0
Hydrogen	44.4	43.3	51.0	48.7									649.3
Oxygen	266.6	259.7	306.0	292.3									3895.7
Planetary Initiative													
MSR													16.1
VAP													7.2
MAO													5.9
LL	10.9	10.9	10.9	10.9									109
CASR													21.64
MSP		6.7		6.7									26.8
SO													11.3
SF/P		15.1											15.1
CNSR		49.8											49.8
NEAR				7.5									7.5
MANNED PHOBOS													
Storables													1446
TOTALS	324.4	386.3	368.7	367.1	0.83	0	0	0	0	0	0	0	6381.48

Table 2-5. Comprehensive Space Station Fluid Requirements (Mars Expedition)

DESCRIPTION	TIMEPHASED FLUID MASS REQUIREMENTS													
	1994 (mt)	1995 (mt)	1996 (mt)	1997 (mt)	1998 (mt)	1999 (mt)	2000 (mt)	2001 (mt)	2002 (mt)	2003 (mt)	2004 (mt)	2005 (mt)	2006 (mt)	
US EXPERIMENTAL PAYLOAD FLUID REQUIREMENTS														
	0	0	2,505	1,581	5,724	2,729	5,409	6,228	3,398	4,505	6,108	2,738	3,605	
OMV (FLIGHTS)	0	0	0	3	4	2	4	4	4	4	4			
Bi-Prop				4	4	2	4	4	4	4	4			
Hydrazine				1.5	2	1	2	2	2	2	2			
Nitrogen				0.2	0.3	0.2	0.3	0.3	0.3	0.3	0.3			
STV (Rev 8 w/o Planetary)	145	166	197	196	239	256	281	261	297	278	321	321	275	
Hydrogen	20.7	23.7	28.1	28.0	34.1	36.6	40.1	37.3	42.4	39.7	45.9	45.9	39.3	
Oxygen	124.3	142.3	168.9	168.0	204.9	219.4	240.9	223.7	254.6	238.3	275.1	275.1	235.7	
Planetary Initiative														
MSR			16.1											
VAP					7.2									
MAO							5.9							
LL								10.9	10.9	10.9	10.9	10.9	10.9	
CASR									21.64					
MSP											6.7		6.7	
SO											11.3			
SF/P														
CNSR														
NEAR														
MARS EXPEDITION														
Storables												549	1415	
												15	14	
TOTALS	145	166	215.6	203.3	258.2	261.9	298.6	284.4	339.2	299.7	362.3	898.6	1725	

Table 2-5. Comprehensive Space Station Fluid Requirements (Mars Expedition) (continued)

DESCRIPTION	TIMEPHASED FLUID MASS REQUIREMENTS												GRAND TOTALS
	2007 (mt)	2008 (mt)	2009 (mt)	2010 (mt)	2011 (mt)	2012 (mt)	2013 (mt)	2014 (mt)	2015 (mt)	2016 (mt)	2017 (mt)	2018 (mt)	
US EXPERIMENTAL PAYLOA	2.523	0.753	0.8	1	0.83	0	0	0	0	0	0	0	50.436
OMV (FLIGHTS)													
Bi-Prop													29.0
Hydrazine													30.0
Nitrogen													14.5
													2.2
STV (Rev 8 w/o Planetary)	311	303	357	341									4545.0
Hydrogen	44.4	43.3	51.0	48.7									649.3
Oxygen	266.6	259.7	306.0	292.3									3895.7
Planetary Initiative													
MSR													16.1
VAP													7.2
MAO													5.9
LL	10.9	10.9	10.9	10.9									109
CASR													21.64
MSP		6.7		6.7									26.8
SO													11.3
SF/P		15.1											15.1
CNSR		49.8											49.8
NEAR				7.5									7.5
MARS EXPEDITION	873	1188	423	829	28								5305
Storables	24	15	5	15									88
TOTALS	1221	1589	796.7	1211	28.83	0	0	0	0	0	0	0	10305.5

Table 2-6. Comprehensive Space Station Fluid Requirements (Lunar Observatories)

			TIMEPHASED FLUID MASS REQUIREMENTS																
DESCRIPTION	1994 (mt)	1995 (mt)	1996 (mt)	1997 (mt)	1998 (mt)	1999 (mt)	2000 (mt)	2001 (mt)	2002 (mt)	2003 (mt)	2004 (mt)	2005 (mt)	2006 (mt)						
US EXPERIMENTAL PAYLOAD FLUID REQUIREMENTS																			
	0	0	2.505	1.581	5.724	2.729	5.409	6.228	3.398	4.505	6.108	2.738	3.605						
OMV (FLIGHTS)	0	0	0	3	4	2	4	4	4	4	4								
Bi-Prop				4	4	2	4	4	4	4	4								
Hydrazine				1.5	2	1	2	2	2	2	2								
Nitrogen				0.2	0.3	0.2	0.3	0.3	0.3	0.3	0.3								
STV (Rev 8 w/o Planetary)	145	166	197	196	239	256	281	261	297	278	321	321	275						
Hydrogen	20.7	23.7	28.1	28.0	34.1	36.6	40.1	37.3	42.4	39.7	45.9	45.9	39.3						
Oxygen	124.3	142.3	168.9	168.0	204.9	219.4	240.9	223.7	254.6	238.3	275.1	275.1	235.7						
Planetary Initiative																			
MSR			16.1																
VAP					7.2														
MAO							5.9												
LL								10.9	10.9	10.9	10.9	10.9	10.9						
CASR									21.64										
MSP																			
SO											6.7		6.7						
SF/P											11.3								
CNSR																			
NEAR																			
LUNAR OBSERVATORIES																			
											178	178	95						
TOTALS	145	166	215.6	203.3	258.2	261.9	298.6	284.4	339.2	299.7	540.3	512.6	391.2						

Table 2-6. Comprehensive Space Station Fluid Requirements (Lunar Observatories) (continued)

		TIMEPHASED FLUID MASS REQUIREMENTS												
	DESCRIPTION	2007 (mt)	2008 (mt)	2009 (mt)	2010 (mt)	2011 (mt)	2012 (mt)	2013 (mt)	2014 (mt)	2015 (mt)	2016 (mt)	2017 (mt)	2018 (mt)	GRAND TOTALS
	US EXPERIMENTAL PAYLOA													
		2.523	0.753	0.8	1	0.83	0	0	0	0	0	0	0	50.436
	OMV (FLIGHTS)													29.0
	Bi-Prop													30.0
	Hydrazine													14.5
	Nitrogen													2.2
	STV (Rev 8 w/o Planetary)	311	303	357	341									4545.0
	Hydrogen	44.4	43.3	51.0	48.7									649.3
	Oxygen	266.6	259.7	306.0	292.3									3895.7
	Planetary Initiative													
	MSR													16.1
	VAP													7.2
	MAO													5.9
	LL	10.9	10.9	10.9	10.9									109
	CASR													21.64
	MSP		6.7		6.7									26.8
	SO													11.3
	SF/P		15.1											15.1
	CNSR		49.8											49.8
	NEAR				7.5									7.5
	LUNAR OBSERVATORIES													
		95	95	95	95	95	95	95	95					1211
	TOTALS	419.4	481.3	463.7	462.1	95.83	95	95	95	0	0	0	0	6123.48

Table 2: 7. Comprehensive Space Station Fluid Requirements (Lunar Base to Mars Evolution)

DESCRIPTION	1994	1995	1996	TIMEPHASED FLUID MASS REQUIREMENTS												2005	2006
	(mt)	(mt)	(mt)	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	(mt)	(mt)	(mt)	(mt)
US EXPERIMENTAL PAYLOAD FLUID REQUIREMENTS																	
	0	0	2,505	1,581	5,724	2,729	5,409	6,228	3,398	4,505	6,108	2,738	3,605				
OMV (FLIGHTS)	0	0	0	3	4	2	4	4	4	4	4						
Bi-Prop				4	4	2	4	4	4	4	4						
Hydrazine				1.5	2	1	2	2	2	2	2						
Nitrogen				0.2	0.3	0.2	0.3	0.3	0.3	0.3	0.3						
STV (Rev 8 w/o Planetary)	145	166	197	196	239	256	281	261	297	278	321	321	275				
Hydrogen	20.7	23.7	28.1	28.0	34.1	36.6	40.1	37.3	42.4	39.7	45.9	45.9	39.3				
Oxygen	124.3	142.3	168.9	168.0	204.9	219.4	240.9	223.7	254.6	238.3	275.1	275.1	235.7				
Planetary Initiative																	
MSR			16.1														
VAP					7.2												
MAO							5.9										
LL								10.9	10.9	10.9	10.9	10.9	10.9				
CASR									21.64								
MSP																	
SO												6.7	6.7				
SF/P												11.3					
CNSR																	
NEAR																	
LUNAR BASE TO MARS *																	
Earth to LEO																	
Earth to LLO										80	20	90	180				
Earth to LMO											70	20	60				
TOTALS	145	166	215.6	203.3	258.2	261.9	298.6	284.4	339.2	379.7	452.3	444.6	536.2				
* These mission requirements include the cryogenic propellants (LOX/LH2) and Argon (for the nuclear/electric propulsion system) delivered from Earth. It does not include the LLOX needed by the Mars Piloted Vehicle delivered to LLO from the Lunar Base.																	

Table 2-7 Comprehensive Space Station Fluid Requirements (Lunar Base to Mars Evolution) (continued)

DESCRIPTION	TIMEPHASED FLUID MASS REQUIREMENTS												GRAND TOTALS
	2007 (mt)	2008 (mt)	2009 (mt)	2010 (mt)	2011 (mt)	2012 (mt)	2013 (mt)	2014 (mt)	2015 (mt)	2016 (mt)	2017 (mt)	2018 (mt)	
US EXPERIMENTAL PAYLOA	2.523	0.753	0.8	1	0.83	0	0	0	0	0	0	0	50.436
OMV (FLIGHTS)													29.0
Bi-Prop													30.0
Hydrazine													14.5
Nitrogen													2.2
STV (Rev 8 w/o Planetary)	311	303	357	341									4545.0
Hydrogen	44.4	43.3	51.0	48.7									649.3
Oxygen	266.6	259.7	306.0	292.3									3895.7
Planetary Initiative													
MSR													16.1
VAP													7.2
MAO													5.9
LL	10.9	10.9	10.9	10.9									109
CASR													21.64
MSP		6.7		6.7									26.8
SO													11.3
SF/P		15.1											15.1
CNSR		49.8											49.8
NEAR				7.5									7.5
LUNAR BASE TO MARS *													
Earth to LEO	40	40	175	110	90	165	110	165	160	165	60	40	1690
Earth to LLO	60			40	10		50		40				350
Earth to LMO						180		15		15			210
TOTALS	424.4	426.3	543.7	517.1	100.8	345	160	180	200	180	60	40	7162.48

and construction of a propellant storage facility in LEO. The elimination of such a facility could reduce the overall life cycle costs of the mission, but this decision would require a detailed trade study. Reference 1-3 includes a discussion of some the important issues and elements required for such an approach.

2.5.2 MANNED MARS MISSION. The Manned Mars Mission propellant requirements are defined in Table 2-5. This mission requires the largest quantity of fluids, with a total greater than 5400 metric tons between the years 2005 and 2011. The peak year, 2006, requires in excess of 1400 metric tons of fluids to be delivered to LEO. This requirement places an enormous demand upon launch and space facilities that must be available by 2006.

2.5.3 LUNAR OBSERVATORY. The Lunar Observatory propellant requirements are defined in Table 2-6. This mission has the most evenly distributed fluid resupply requirements. Two years of 178 metric tons and nine years of 95 metric tons (per year) of fluids, for a grand total of 2011 metric tons between 2004 and 2014, gives this mission the most consistent propellant resupply schedule of the Code Z missions.

2.5.4 LUNAR OUTPOST TO EARLY MARS EVOLUTION. The Lunar Outpost to Early Mars Evolution propellant requirements are defined in Table 2-7. This mission has the "longest" timephased fluid requirements. The first year of fluid requirements is 2003 with moderate (relative to other Code Z missions) fluid requirements continuing through 2018. Between the years of 2003 and 2018, a total of 2250 metric tons of fluids are required for this mission model. The fluid storage facility to support this mission model will have to be designed for long life and extended space exposure.

2.6 FLUID REQUIREMENTS SUMMARY

Several observations can be made following the definition of all SS related fluid requirements. First, there are a large number of fluid users, which require a variety of fluids and delivery/storage concepts and schedules. Secondly, the propellants required for NASA's STV, Planetary, and Code Z missions are enormous.

The storage methods must accommodate fluids ranging from a high pressure gas to a subcooled liquid (and superfluid helium). The requirements begin in the year 1994, reach a maximum of nearly 1600 metric tons in the year 2008 (for the Mars Expedition), and "trail off" to the year 2018, as currently planned.

3

FLUID MANAGEMENT OPTIONS

This section describes alternate methods of providing fluid (both SS and co-orbiting platform) users with fluid requirements. Since the storage method design process for hazardous and flammable fluids at the SS will likely be driven by safety concerns (human environment), a safety analysis provided an initial basis for comparison. Location trade matrices are presented for individual experiments, which consider operations, safety, and performance.

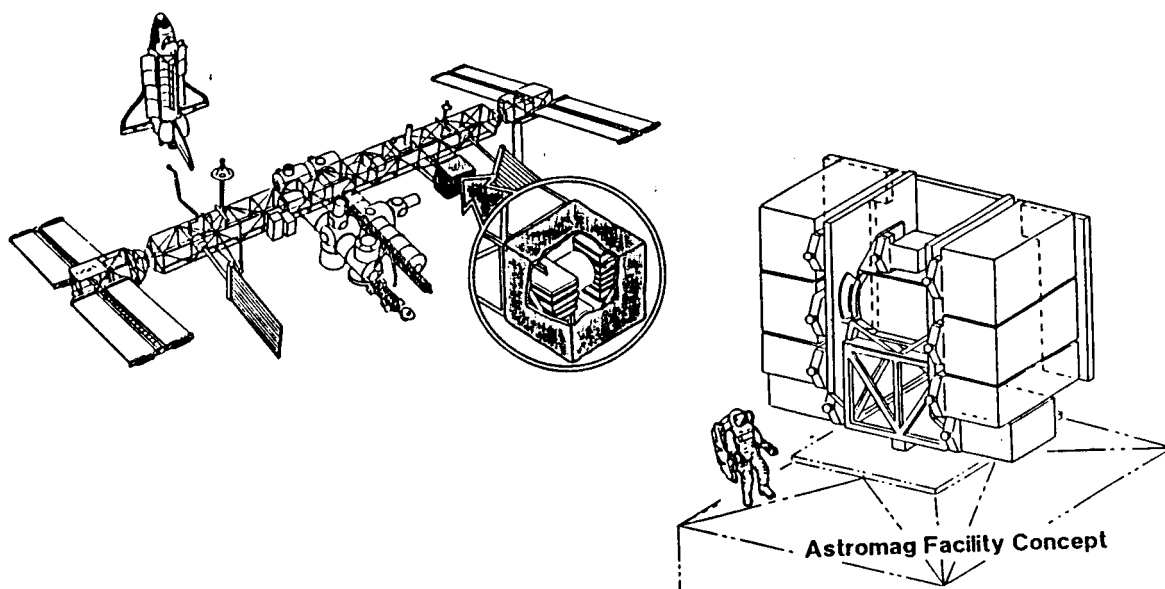
Alternatives for the "experimental users" included; bottle changeout (ORUs recharged either at the SS or replaced by full ORUs delivered from earth by the STS), using hard lines connecting fluid containers or carriers with each individual user, or transporting users to a fluid carrier (centrally located on the SS) for refilling.

Conceptual design concepts of fluid carriers have been defined to allow transport of all fluids from earth to the SS, to support the fluid requirements. Figure 3-1 contains an illustration and description of the ASTROMAG experiment, which will be attached to the baseline SS boom. Figure 3-2 includes the same for the LDR experiment, which will be a free-flying experiment, and is assumed (with several other free-flyers) to be serviced from the SS for this study. The following experiments were considered in this study:

1. ASTROMAG* - Astrophysics Magnet Facility
2. DXS* - Diffuse X-Ray Spectrometer
3. LAMAR* - Large Area Modular Array
4. STO/SIG* - Solar Terrestrial Observatory/Solar Instrument Group
5. STO/PIG* - Solar Terrestrial Observatory/Plasma Instrument Group
6. STO/SS - Solar Terrestrial Observatory/Space Station Attached
7. AXAF- Advanced X-Ray Astrophysics Facility
8. GRO - Gamma Ray Observatory
9. LDR - Large Deployable Reflector
10. SBAR - Space Based Antenna Range
11. SIRTf - Space Infrared Telescope Facility
12. 3S - Space Station Spartan
13. STO/POP - Solar Terrestrial Observatory/Polar Orbiting Platform
14. XGP - Experimental Geo Platform

* Denotes experiments which are planned to be attached to the IOC SS.

Cryogenic propellant provisioning is treated separately, and includes a discussion of propellant



TITLE: Particle Astrophysics Magnet Facility (ASTROMAG)

OBJECTIVE: 1) Study the origin and evolution of matter in the Milky Way, 2) Search for antimatter and dark matter candidates, and 3) Study the origin and acceleration of the relativistic particle plasma and its effects on the dynamics and evolution of the galaxy.

DESCRIPTION: ASTROMAG is a high energy astrophysics tool. The primary components consist of a core magnet, a liquid helium dewar and particle tracking detectors.

LOCATION: Space Station attached payload.

SERVICING REQUIREMENTS:

Consumable replenishment

-Superfluid helium

-Rare gas mixtures (possibly)

Experiment replacement and/or upgrade

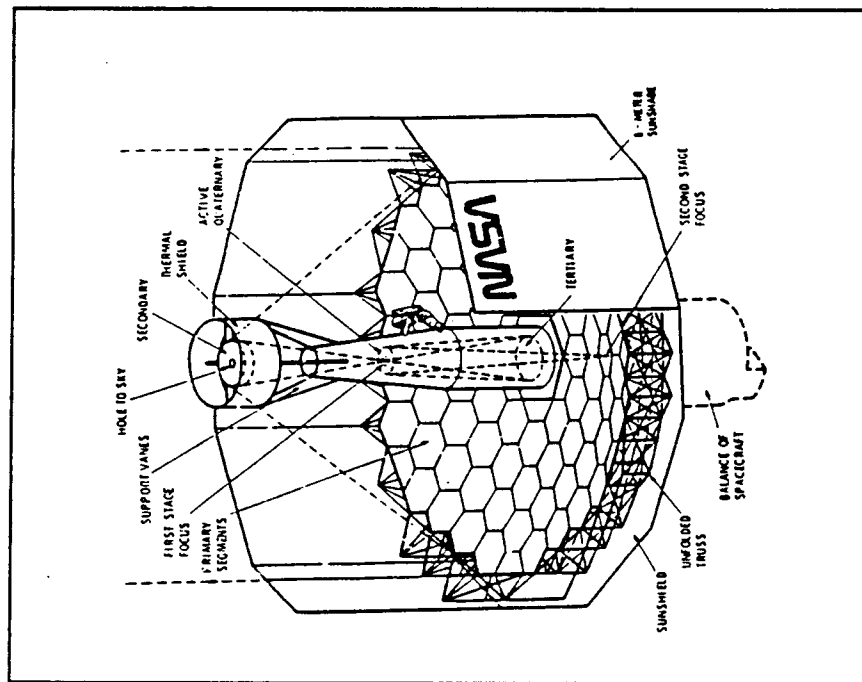
Instrument calibration and alignment

IDENTIFIED CONSUMABLE REPLENISHMENT APPROACH:

Superfluid helium- Translate tanker to ASTROMAG attachment site on the Space Station.

Rare gas- Modular gas bottle changeout, recharge existing gas bottle or use sealed instruments and replace them entirely.

Figure 3-1. ASTROMAG Space Station Attached Experimental Payload



TITLE: Large Deployable Reflector (LDR)

OBJECTIVE: Conduct submillimeter-infrared astronomical observations of a wide variety of astrophysical phenomena (spectral region between 30 to 1000 microns).

DESCRIPTION: LDR is a 20 meter diameter filled-aperture reflecting telescope composed of an optical system, an instrument module, a telescope support module and a resource module.

LOCATION: LDR will be attached to the Space Station during construction and will be transported to its operating orbit (700 km circular, 28.5 degree inclination) via an OMV.

SERVICING REQUIREMENTS:

- On-orbit assembly and checkout
- Consumable replenishment
 - Superfluid helium
 - ORU changeout

IDENTIFIED CONSUMABLE REPLENISHMENT APPROACH:

Superfluid helium- An OMV equipped with a Flight Telerobotic Servicer (FTS) will carry the superfluid helium (and ORU's) to the LDR for in-situ servicing. Approximately 225 hours of EVA will be required for on-orbit assembly however no EVAs will be needed for consumable replenishment.

Figure 3-2. LDR (Large Deployable Reflector) Experiment Description

provisioning from the SS or from a co-orbiting platform. In addition, detailed thermodynamic analyses of LH2 and LO2 transfer and storage processes have been reported. These results illustrate the wide range of steady-state and transient tankset performance for a variety of operating conditions, and provided the basis for propellant transfer operation scenarios included in Section 4 of this report.

3.1 SYSTEM SAFETY ISSUES, REQUIREMENTS, AND IMPLICATIONS

The System Safety effort during the conduct of this study involved several different types of activities. Included were information and data searches, trade studies, and a Preliminary Hazard Analysis (PHA). References 3-1 through 3-13 were used to provide a basis for the safety analysis. The experiments listed previously were evaluated.

3.1.1 PRELIMINARY HAZARDS ANALYSIS. GDSS used NASA's typical methodology of system safety analyses (Reference 3-10, Instructions for Preparation of Hazard Analyses for the Space Station) to evaluate the hazards associated with fluids in close proximity to the space station and also fluids which may be somewhat isolated from the station. To begin the process, GDSS initiated a preliminary hazard analysis as described in Refer. 3-10. The analysis is presented on the following PHA worksheets (Preliminary Hazards Analysis 1 through 5), in Tables 3-1 to 3-5.

Table 3-1. PHA 1, Fluid Impingement on Crew, Payloads and Space Vehicles

PHA NO. 1

FLUIDS STUDY PRELIMINARY HAZARD ANALYSIS

SHEET 1 OF 1

MISSION PHASE: _____

ENGINEER: _____

SUBSYSTEM OR OPERATION: _____

DATE: _____

EFFECTIVITY: _____

HAZARDOUS CONDITION	HAZARD CAUSE	HAZARD EFFECT	HAZARD LEVEL	SAFETY REQUIREMENTS	HAZARD CONTROL
Fluid Impingement on crew, payloads and space vehicles.	1. Spill during handling. 2. Inadvertent venting. 3. Container leak/rupture.	Injury to crew Equipment damage	CR	1. Crew should wear protective suit during handling. 2. Fluids should be stored TBD distance away from the habitable module and other critical equipment. 3. Blast shields should be provided around fluid tanks. 4. All venting should be directed away from critical equipment and personnel access/evacuation routes.	TBD

Note: Hazard Levels; CA-Catastrophic, CR-Critical

Table 3-2. PHA 2, Fire/Explosion

PHA NO. 2

FLUIDS STUDY PRELIMINARY HAZARD ANALYSIS

SHEET 1 OF 1

MISSION PHASE: _____

ENGINEER: _____

SUBSYSTEM OR OPERATION: _____

DATE: _____

EFFECTIVITY: _____

HAZARDOUS CONDITION	HAZARD CAUSE	HAZARD EFFECT	HAZARD LEVEL	SAFETY REQUIREMENTS	HAZARD CONTROL
Fire/Explosion	1. Mixing of fuel and oxidizer in the presence of an ignition source. 2. Static electricity due to high fluid velocities. 3. Oxidation of the exposed fluid contacting surfaces. 4. Ignition of materials in the vicinity of fluids.	Injury to crew. Damage to equipment	CA	1. a. Fuels and oxidizers must be stored separately. 1. b. Blast shields must be provided around the tanks. 1. c. Fluid mixing should be prevented during venting. 2. All systems should be bonded to prevent accumulation of static electricity. 3. Only compatible materials should be used. 4. Only non-flammable materials should be used.	TBD

Note: The term "Bonded" in this case refers to the electrical grounding of all components.

Table 3-3. PHA 3, Loss of Habitable Environment

PHA NO. 3

FLUIDS STUDY PRELIMINARY HAZARD ANALYSIS

SHEET 1 OF 1

MISSION PHASE: _____

ENGINEER: _____

SUBSYSTEM OR OPERATION: _____

DATE: _____

EFFECTIVITY: _____

HAZARDOUS CONDITION	HAZARD CAUSE	HAZARD EFFECT	HAZARD LEVEL	SAFETY REQUIREMENTS	HAZARD CONTROL
Loss of habitable environment	1. Contamination/corrosion from fluid. 2. Impingement of fluid on critical support equipment. 3. Fire/explosion resulting in destruction of habitat or critical support systems.	Loss of crew life	CR	1. All fluids should be located TBD feet from habitable modules. 2. Blast shields should be provided around habitable modules and/or fluid tanks. 3. All venting should be directed away from the habitable modules.	TBD

Table 3-4. PHA 4, Fluid System Leak/Rupture

PHA NO. 4

FLUIDS STUDY PRELIMINARY HAZARD ANALYSIS

SHEET 1 OF 1

MISSION PHASE: _____

ENGINEER: _____

SUBSYSTEM OR OPERATION: _____

DATE: _____

EFFECTIVITY: _____

HAZARDOUS CONDITION	HAZARD CAUSE	HAZARD EFFECT	HAZARD LEVEL	SAFETY REQUIREMENTS	HAZARD CONTROL
Fluid System Leak/Rupture	1. Failure of seals at interface during transfer. 2. Meteor impact on containers. 3. Container damage during handling. 4. Failure of venting system to reduce container internal pressure.	Injury to crew. Damage to equipment	CR	1. Crew should wear suits compatible with fluids. 2. Tanks must be provided with meteor protection. 3. Plans shall be developed to remove damaged containers. 4. Redundant vent system should be used. 5. Leak detection system required.	TBD

Table 3-5. PHA 5, Release of Corrosive, Toxic, Flammable, or Cryogenic Fluid

PHA NO. 5 SHEET 1 OF 1
 FLUIDS STUDY PRELIMINARY HAZARD ANALYSIS
 MISSION PHASE: _____ ENGINEER: _____
 SUBSYSTEM OR OPERATION: _____ DATE: _____
 EFFECTIVITY: _____

HAZARDOUS CONDITION	HAZARD CAUSE	HAZARD EFFECT	HAZARD LEVEL	SAFETY REQUIREMENTS	HAZARD CONTROL
Release of corrosive, toxic, flammable, or cryogenic fluid	1. Normal or inadvertent venting.	Injury to crew.	CR	1. Leak detection system should be installed.	TBD
	2. Container leakage/rupture.	Damage to equipment		2. Blast shields should be provided around fluid tanks.	
	3. Spill during handling.			3. Spill handling procedure should be developed for each fluid.	
	4. Failure of venting system to reduce container internal pressure.			4. Redundant vent system should be provided.	

The Preliminary Hazard Analysis (PHA) has identified areas where additional work and analyses will

have to be accomplished in order to understand the hazardous events more fully and determine what design requirements will be necessary to control the hazards to an acceptable level.

1. Hazards associated with spills in the microgravity and vacuum environment.
2. Contamination or explosion that may lead to the loss of habitable environment.
3. Safe quantities/distances for the separation of fluids during storage.

Spills

Spills represent a significant hazard to Space Station personnel and hardware. Hazards to personnel exist through inadvertent contact and subsequent contamination of the EVA suit from hazardous fluids during handling of containers or transfer of fluids. Personnel will also be exposed to the hazardous fluids during spill removal and cleaning operations. Spills of hazardous fluids could result from various causes as follows:

- a. Damage to containers during transfer to and from Space Station based experiments.
- b. Overfilling and excessive venting.
- c. Leakage or rupture of containers, lines, or plumbing.
- d. Inadvertent opening of fill/drain valves or relief valves.

Spills may result in a gaseous cloud that remains in the vicinity of the leak or migrates to other areas (such as the habitable modules). Spills may be in a solid or liquid form depending on the temperature and pressure of the vented fluid and the environment.

The following are the recommended safety requirements:

- a. Fluid separation is required to isolate the spills. Ideally, non-compatible fluids should not be stored together and fuels and oxidizers should not be stored together.
- b. Hazardous fluids should be stored at least TBD (to be defined by possible future NASA studies) feet from habitable modules and critical support equipments.
- c. Spill clean-up procedures should be developed.

Contamination

Contamination of life support equipment or explosion of gases within a module could lead to a close down of one or more habitable modules. The following are the recommended safety requirements:

- a. Sufficient structure should surround the fluid tanks to prevent blast fragments damaging habitable modules or other critical equipment.
- b. All fluid venting should be directed away from habitable modules.
- c. Fluids with the highest explosive power should be located at the farthest distance from the habitable modules.

Safe Quantities and Separation Distances

To reduce the hazards resulting from an explosion of the fluid tanks, criteria is required for safe quantities/distances for storage on Space Station. A preliminary review indicates that this criteria exists only for the storage of fluids in earth environment. Tables 3-6, 3-7 and 3-8 summarize this information (this information was taken from Reference 3-2).

Table 3-6. Propellant Hazards and Compatibility Groups

PROPELLANTS	HAZARD GROUP	COMPATIBILITY GROUP
Anhydrous Ammonia	I	C
Nitrogen Tetroxide	I	A
Liquid Oxygen	II	A
Hydrazine	III	C
Liquid Hydrogen	III	C
Monomethylhydrazine	III	C

Notes:

1. Group I: Relatively Low Fire Hazard
2. Group II: Fire Hazard
3. Group III: Fragment and Deflagration Hazard
4. Group A: Strong Oxidizers
5. Group C: Fuels

Table 3-7. Separation Distances for Hazard Groups, I - II - III (In Terrestrial Environment)

POUNDS OF PROPELLANT INTRAGROUP		INHABITED	
OVER	NOT OVER	BUILDINGS DISTANCE - FT	DISTANCE - FT
0	100	30-60-80	25-30-30
900	1,000	60-120-150	45-60-60
9,000	10,000	90-180-240	70-90-90
90,000	100,000	135-270-365	105-135-135

COMPATIBLE FLUIDS STORAGE:

- FOR SAME HAZARDS GROUP: USE INTRAGROUP DISTANCE
- FOR DIFFERENT HAZARD GROUP: USE GREATEST INTRAGROUP DISTANCE

INCOMPATIBLE FLUIDS STORAGE:

- USE GREATEST INHABITED BUILDING DISTANCE

PIPELINES:

- MINIMUM OF 25 FT FROM INHABITED BUILDINGS FOR TRANSFER OF FLUIDS IN GROUP II AND III

Table 3-8. Separation Classification of Space Station Fluids

COMPRESSED GASES

a. NON-FLAMMABLE	b. FLAMMABLE	c. NON-FLAMMABLE, OXIDIZER
Argon	Hydrogen	Oxygen
Helium	Methane	
Nitrogen		
Xenon		

NON-FLAMMABLE, REFRIGERATED

Liquid Helium
Liquid Nitrogen

Notes:

1. Oxygen and Fuel containers shall be separated by at least 20 feet.
 2. Flammable gases shall be separated from other fluids and between themselves by at least 20 feet.
-

As can be seen from this data we began our safety analysis by first identifying the fact that some of the proposed propellants which will be used at the Space Station are hazardous in nature within an earth environment. Micro-gravity and vacuum environment around the Space Station presents concerns that are different from the earth storage concerns.

Blast fragments will travel at very high velocities making separation distances ineffective without blast fragment protection. Therefore, the separation distances for fluids at the Space Station will have to be based on spill containment, contamination, compatibility of fluids and the effectiveness of blast protection.

The following are the recommended safety requirements to be used in method comparison/selection:

- a. All fluids should be located TBD feet away from the habitable modules.
- b. All hazardous fluid tanks should be designed to minimize the cumulative explosion effects.
- c. Non-compatible fluids should not be stored together.

The key results of the safety trade studies can be summarized by the following six (6) Safety Design Considerations for the development of an overall Fluid Management concept for the Space Station:

1. Separate Fuels and Oxidizers
2. Minimize Extra Vehicular Activity (EVA)

3. Design for expedient EVA if necessary (no protrusions, no sharp edges, etc.)
4. Protect internal/external depot components from contamination
5. Protect experiments from contamination
6. Plan for spills/leaks (develop de-contamination procedures for equipment and EVA suits).

3.2 ALTERNATE EXPERIMENTAL FLUID PROVISIONING APPROACHES

Figure 3-3 shows an "early concept" of a fluids carrier with removable bottles mounted to the Space Station. This approach, which separates different types of fluids into dedicated carriers, offers the advantage of providing separation between incompatible fluids, which may otherwise create a hazard, if both should leak in proximity to one another. The bottles could then be removed from the carrier and exchanged by EVA with the experiment bottles (which would be empty). Figure 3-4 shows an RMS removing a gas bottle or fluid tank and also shows a representation of the use of a flexible transfer line connecting the fluids storage facility and an experimental user. The fluid carriers could bring up filled bottles for exchange with empty fluid containers in either the carrier or on the experiment. The empty containers could be returned to Earth in the carrier, recharged, and used on future resupply missions.

A variation of this approach would still changeout the experiment bottles, but rather than replacing the bottles with identical ORUs, the empty experiment bottles could be recharged from "bulk" size bottles/tanks within the carrier.

Running a flexible line to the experiment would allow for easy resupply of a variety of experiments, but EVA with long lines would be difficult and contamination/cleaning of a "common" line would result in additional fluid use and operations, since the line would require venting down between resupply periods (unless individual lines were used to accommodate each different fluid). Experience with astronaut spacesuit umbilicals on Skylab indicates that EVA management of flexible lines becomes difficult beyond about 25 ft. Not only does the astronaut get tangled in the line, but the line can easily get tangled around the structure. Recharging the experiment bottles using a flexible line from the fluid carrier bottles/tanks to the individual experiments is not expedient from an operational standpoint.

Bottle changeout does not require transfer lines. The disadvantage is that bottle transfer and changeout could require extensive EVA planning and more complicated design considerations for the experiments to allow for EVA access.

Another method would use fixed (hard plumbed) fluid lines from the fluid carrier to each experiment,

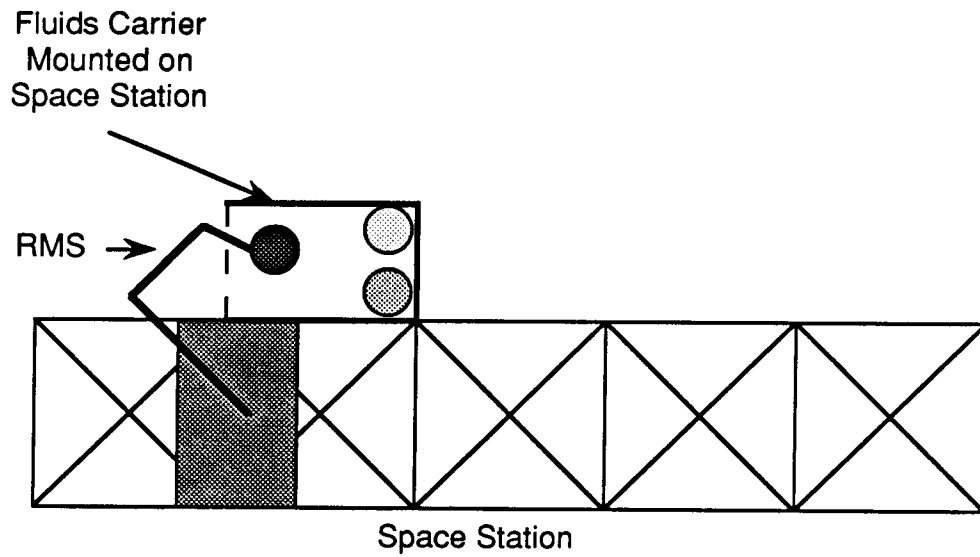


Figure 3-3. Fluids Carrier Mounted on the Space Station

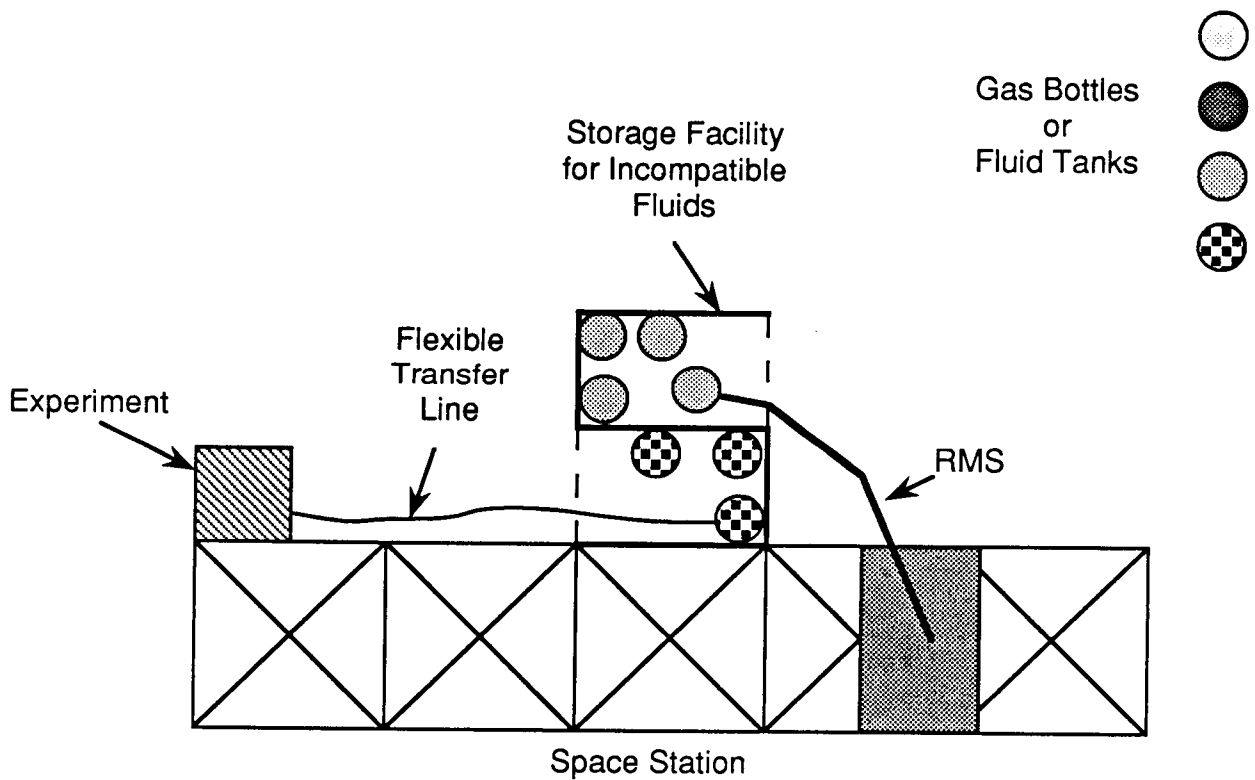


Figure 3-4. Storage of Incompatible Fluids and Use of a Flexible Transfer Line to Provide Fluids to Experimental Users

but this approach is impractical during initial IOC experiments due to the infrequency of most of the resupply operations. In addition, installation of the plumbing system would be an enormous task both operationally and economically, and is somewhat "inflexible" to accommodate Space Station/truss growth. Also, this system would be more susceptible to fluid and thermal leaks. However, as use rates grow for a particular fluid, an integrated plumbing approach may be justifiable. These possibilities are discussed later for the individual experiments. The helium and nitrogen fluid approaches which are envisioned by NASA at this time are described in the following paragraphs, but hydrazine, xenon, argon, methane, and rare gases do not have a similar systems defined by NASA to date.

3.2.1 SPECIFIC FLUID CONCERNS/ISSUES

Helium Provisioning

Superfluid and liquid helium is desirable for use in satellite cooling systems because of its unique thermal properties. The unique physical properties and behavior of liquid helium (and superfluid helium) and the unique requirement for high flow rate, zero gravity transfer renders experience gained with other fluids inadequate.

The preliminary conceptual design of an on-orbit helium replenishment approach has been conducted and is documented in the final report of the Superfluid Helium Tanker Study (SFHT) (NASA JSC) (see Reference 3-14) and the preliminary report of the Space Station Based Liquid Helium Servicing Facility (LHSF) (NASA -GSFC) (see Reference 3-15). These concepts are based on the in-situ fluid resupply philosophy. This approach offers more flexibility at a greater initial manpower cost (until processes can be automated). These concepts are based on a 10,000 liter spherical dewar (the reference showed that the spherical dewar design minimizes mass and life cycle costs). The fluid transfer system for this concept consists of a liquid acquisition device (LAD), a thermomechanical (TM) pump, SFHT plumbing, flexible transfer lines and user plumbing.

Initial operations have been established for the SFHT. Delivery to Space Station will be accomplished via the STS (with an ELV/OMV as an alternative). The SFHT is equipped with an end effector so that it can be attached to grapple fixtures at the Space Station, or so that a user can be attached to the SFHT. The grapple fixture and end effector combination allows for a variety of basing methods. This design of the SFHT will require an EVA to connect and disconnect the electrical and fluid lines. Users will be transported to the Space Station via an OMV or the SFHT will have to be used onboard the Shuttle so that the supporting EVAs may be performed. Follow-on concepts will have automatic electrical and fluid connections which will allow for teleoperated helium replenishment.

The development of an on-orbit liquid helium storage and transfer capability is urgent because of the potential of several applications. In particular, the Particle Astrophysics Magnet Facility (ASTROMAG) (see Figure 3-1), under development at GSFC, and the Space Infrared Telescope Facility (SIRTF), under development at Ames. Of these two experiments, the SIRTF is the major driver because it requires greater quantities of liquid helium, although ASTROMAG may be deployed earlier.

At the IOC SS, ASTROMAG will be attached, and delivered full of helium. Free-flyers which need helium must either be brought to the earth, the STS, or to the SS (if a helium storage facility exists) for replenishing. If growth results in large enough use rates of LHe, a LHe carrier could be attached to the SS truss near the CSF, and hard plumbed to a CSF fluid interface. It is imperative to minimize the length of fluid transfer lines which connect LHe supply and receiver tanks, to reduce the LHe required to prechill the lines prior to transfer operations. Long lines result in large thermal masses, and hence a great deal of sensible heat which must be removed, which is realized finally in the form of LHe boiloff/losses.

Nitrogen

An integrated nitrogen subsystem (INS) is baselined for the IOC SS, which will basically consist of a nitrogen "fluid bus" on the SS structure, designed to provide multiple users with nitrogen.

3.2.2 EXPERIMENT FLUID PROVISIONING APPROACH COMPARISONS. The results of a qualitative trade study is presented in this section, where the advantages and disadvantages of nine fluid provisioning approaches for each type of experiment from the stand point of crew/Space Station safety, and EVA/IVA operations. These criteria are the two greatest factors in determination of a preferred approach.

Tables 3-9 through 3-22 document the results of this trade study. The approach used for this trade was to develop a matrix of the different fluids used by each experiment and then identify advantages and disadvantages of the various provisioning approaches.

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Table 3-9. ASTROMAG Experiment Fluid Provisioning Approach Matrix

Experiment Title: 5. ASTROMAG		Description/location: Liquid Helium & Gas Servicing/Attached to Space Station		
Fluids	Opt.	Description	Advantages	Disadvantages
Misc. Fluids	1	Bottle changeout (w/indiv. exp'mts)	1. Smaller quantities of fluids.	1. More operations. 2. EVA/IVA operations more complex.
	2	Fluids manifolded (exp'mt moved to depo. refilled, and replaced)	1. Single point of connect/disconnect. 2. EVA centralized.	1. Equipment more susceptible to spills/leaks. 2. Mixture of fluids. 3. Contamination of depot area from purging. 4. Movement of bulky experiment to depot area.
	3	Depot plumbed to exp'mts	1. Does not require EVA. 2. No connecting/disconnecting.	1. Equipment more susceptible to leaks.
	4	Move bottle to user, refill user, rtn. bottle to depot	1. One servicing tank.	1. Sloshing. 2. EVA connecting/disconnecting. 3. Contamination of payload.
	5	Flexible line from depot bottle/dewar to the user	1. No transport of fluids in tanks.	1. Equipment more susceptible to spills/leaks. 2. Contamination of depot area from purging. 3. Entanglement of crew with lines. 4. Entanglement of lines with structure.
LHe & LHeI	1	Move dewar to user, x-fer (like Option 4 above)	1. One servicing tank.	1. Transport of large quantities. 2. Sloshing. 3. EVA connecting/disconnecting. 4. Contamination of payload.
	2	Locate LHe dewar at prime user(s) location	1. One servicing tank.	1. Sloshing. 2. EVA connecting/disconnecting. 3. Contamination of payload.
	3	Changeout of small dewars at experiment from depot	1. Smaller quantity. 2. Some robotic activity.	1. Servicing in vicinity of other tanks (venting). 2. Contamination of depot area. 3. Contamination of depot area.
	4	Use small (i.e. 2,000 ltr) dewar, "shuttle" fluid req'd	1. One servicing tank.	1. Sloshing. 2. Connecting/disconnecting. 3. Contamination of depot area.

Table 3-9 is a summary of the trade done for the ASTROMAG experiment. With this experiment the most advantageous fluid management approach would be to have the experiment hard plumbed to a storage tank. This reduces EVA operations and thus reduces the risk to crew members. For the servicing of ASTROMAG, ORUs are not practical because of the large LHe replenishing requirements, and would result in frequent disturbances to ASTROMAG operation (proximity constraints require no movement of ferrous materials within three meters of ASTROMAG during operation). The replenishing of fluid should be coordinated with other ORU changeout, which would also help minimize disturbances to ASTROMAG experiments. As mentioned previously, LHe transfer line

lengths must be kept as short as possible, or eliminated where possible.

Tables 3-10 through 3-13 summarize the results of the trades done for several other experiments which are attached to the SS; DXS, LAMAR, STO/SIG, and STO/PIG. With these experiments, the most advantageous fluid management approach for miscellaneous fluids would be to have the depot plumbed to each individual experiment. This reduces EVA operations, and thus reduces the risk to crew members.

Table 3-10. DXS Experiment Fluid Provisioning Approach Matrix

Experiment Title: 7. DXS				
Description/Location: P-10, Argon and Methane Gas Servicing/Attached to Space Station				
Fluids	Opt.	Description	Advantages	Disadvantages
Misc. Fluids	1	Bottle changeout (w/indiv. exp'mts)	1. Smaller quantities of fluids.	1. More operations. 2. EVA/IVA operations more complex.
	2	Fluids manifolded (exp'mt moved to depo, refilled, and replaced)	1. Single point of connect/disconnect. 2. EVA centralized.	1. Equipment more susceptible to spills/leaks. 2. Mixture of fluids. 3. Contamination of depot area from purging. 4. Movement of bulky experiment to depot area.
	3	Depot plumbed to exp'mts	1. Does not require EVA. 2. No connecting/disconnecting.	1. Equipment more susceptible to leaks.
	4	Move bottle to user, refill user, rtn. bottle to depot	1. One servicing tank.	1. Sloshing. 2. EVA connecting/disconnecting. 3. Contamination of payload.
	5	Flexible line from depot bottle/dewar to the user	1. No transport of fluids in tanks.	1. Equipment more susceptible to spills/leaks. 2. Contamination of depot area from purging. 3. Entanglement of crew with lines. 4. Entanglement of lines with structure.
LHe & LHeII	1	Move dewar to user, x-fer (like Option 4 above)	N/A	
	2	Locate LHe dewar at prime user(s) location		
	3	Changeout of small dewars at experiment from depot		
	4	Use small (i.e. 2,000 ltr) dewar, "shuttle" fluid req'd		

Table 3-11. LAMAR Experiment Fluid Provisioning Approach Matrix

Experiment Title: 10. LAMAR		Description/location: Xenon and Methane Gas Servicing/Attached to Space Station		
Fluids	Opt.	Description	Advantages	Disadvantages
Misc. Fluids	1	Bottle changeout (w/indiv. exp'mts)	1. Smaller quantities of fluids.	1. More operations. 2. EVA/IVA operations more complex. 3. Radioactivity
	2	Fluids manifolded (exp'mt moved to depo, refilled, and replaced)	1. Single point of connect/disconnect. 2. EVA centralized.	1. Equipment more susceptible to spills/leaks. 2. Radioactivity 3. Contamination of depot area from purging. 4. Movement of bulky experiment to depot area.
	3	Depot plumbed to exp'mts	1. Does not require EVA. 2. No connecting/disconnecting.	1. Equipment more susceptible to leaks.
	4	Move bottle to user, refill user, rtn. bottle to depot	1. One servicing tank.	1. Sloshing. 2. EVA connecting/disconnecting. 3. Contamination of payload. 4. Radioactivity
	5	Flexible line from depot bottle/dewar to the user	1. No transport of fluids in tanks.	1. Equipment more susceptible to spills/leaks. 2. Contamination of depot area from purging. 3. Entanglement of crew with lines. 4. Entanglement of lines with structure.
LHe & LHeI	1	Move dewar to user, x-fer (like Option 4 above)	N/A	
	2	Locate LHe dewar at prime user(s) location		
	3	Changeout of small dewars at experiment from depot		
	4	Use small (i.e 2,000 ltr) dewar, "shuttle" fluid req'd		

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Table 3-12. STO/SIG Experiment Fluid Provisioning Approach Matrix

Experiment title: 12. STO/SIG				
Description/location: Nitrogen Gas Servicing/Attached to Space Station				
Fluids	Opt.	Description	Advantages	Disadvantages
Misc. Fluids	1	Bottle changeout (w/indiv. exp'mts)	1. Smaller quantities of fluids.	1. More operations. 2. EVA/IVA operations more complex.
	2	Fluids manifolded (exp'mt moved to depo, refilled, and replaced)	1. Single point of connect/disconnect. 2. EVA centralized.	1. Equipment more susceptible to spills/leaks. 2. Mixture of fluids. 3. Contamination of depot area from purging. 4. Movement of bulky experiment to depot area.
	3	Depot plumbed to exp'mts	1. Does not require EVA. 2. No connecting/disconnecting.	1. Equipment more susceptible to leaks.
	4	Move bottle to user, refill user, rtn. bottle to depot	1. One servicing tank.	1. Slashing. 2. EVA connecting/disconnecting. 3. Contamination of payload.
	5	Flexible line from depot bottle/dewar to the user	1. No transport of fluids in tanks.	1. Equipment more susceptible to spills/leaks. 2. Contamination of depot area from purging. 3. Entanglement of crew with lines. 4. Entanglement of lines with structure.
LHe & LHeI	1	Move dewar to user, x-fer (like Option 4 above)	N/A	
	2	Locate LHe dewar at prime user(s) location		
	3	Changeout of small dewars at experiment from depot		
	4	Use small (i.e. 2,000 ltr) dewar, "shuttle" fluid req'd		

Table 3-13. STO/PIG Experiment Fluid Provisioning Approach Matrix

Experiment Title: 13. STO/PIG		Description/location: Argon and Xenon Gas Servicing/Attached to Space Station		
Fluids	Opt.	Description	Advantages	Disadvantages
Misc. Fluids	1	Bottle changeout (w/indiv. exp'mts)	1. Smaller quantities of fluids.	1. More operations. 2. EVA/IVA operations more complex.
	2	Fluids manifolded (exp'mt moved to depo. refilled, and replaced)	1. Single point of connect/disconnect. 2. EVA centralized.	1. Equipment more susceptible to spills/leaks. 2. Mixture of fluids. 3. Contamination of depot area from purging. 4. Movement of bulky experiment to depot area.
	3	Depot plumbed to exp'mts	1. Does not require EVA. 2. No connecting/disconnecting.	1. Equipment more susceptible to leaks.
	4	Move bottle to user, refill user, rtn. bottle to depot	1. One servicing tank.	1. Sloshing. 2. EVA connecting/disconnecting. 3. Contamination of payload.
	5	Flexible line from depot bottle/dewar to the user	1. No transport of fluids in tanks.	1. Equipment more susceptible to spills/leaks. 2. Contamination of depot area from purging. 3. Entanglement of crew with lines. 4. Entanglement of lines with structure.
LHe & LHeII	1	Move dewar to user, x-fer (like Option 4 above)	N/A	
	2	Locate LHe dewar at prime user(s) location		
	3	Changeout of small dewars at experiment from depot		
	4	Use small (i.e. 2,000 ltr) dewar "shuttle" fluid req'd		

Tables 3-14 through 3-22 contain comparisons for the unattached experiments. These experiments are not attached to the SS, therefore, the Options shown do not include "Depot Plumbed to Experiments".

The best method of resupply appears to be based on moving the experiment to the SS, and refilling it

through a fluid interface panel, which is connected to a bulk supply of fluid in a fluid carrier located on the SS truss.

Table 3-14. STO/SS Experiment Fluid Provisioning Approach Matrix

Experiment Title: 14. STO/SS				
Description/location: Nitrogen Gas Servicing/Attached to Space Station				
Fluids	Opt.	Description	Advantages	Disadvantages
Misc. Fluids	1	Bottle changeout (w/indiv. exp'mts)	1. Smaller quantities of fluids.	1. More operations. 2. EVA/IVA operations more complex.
	2	Fluids manifolded (exp'mt moved to depo, refilled, and replaced)	1. Single point of connect/disconnect. 2. EVA centralized.	1. Equipment more susceptible to spills/leaks. 2. Mixture of fluids. 3. Contamination of depot area from purging. 4. Movement of bulky experiment to depot area.
	3	Depot plumbed to exp'mts	1. Does not require EVA. 2. No connecting/disconnecting.	1. Equipment more susceptible to leaks.
	4	Move bottle to user, refill user, rtn. bottle to depot	1. One servicing tank.	1. Sloshing. 2. EVA connecting/disconnecting. 3. Contamination of payload.
	5	Flexible line from depot bottle/dewar to the user	1. No transport of fluids in tanks.	1. Equipment more susceptible to spills/leaks. 2. Contamination of depot area from purging. 3. Entanglement of crew with lines. 4. Entanglement of lines with structure.
LHe & LHeI	1	Move dewar to user, x-fer (like Option 4 above)	N/A	
	2	Locate LHe dewar at prime user(s) location		
	3	Changeout of small dewars at experiment from depot		
	4	Use small (i.e. 2,000 ltr) dewar "shuttle" fluid req'd		

Table 3-15. AXAF Experiment Fluid Provisioning Approach Matrix

Experiment Title: 18. AXAF				
Description/location: Liquid Helium Servicing/Not Attached to Space Station				
Fluids	Opt.	Description	Advantages	Disadvantages
Misc. Fluids	1	Bottle changeout (w/indiv. exp'mts)	N/A	
	2	Fluids manifolded (exp'mt moved to depo, refilled, and replaced)		
	3	Depot plumbed to exp'mts		
	4	Move bottle to user, refill user, rtn. bottle to depot		
	5	Flexible line from depot bottle/dewar to the user		
LHe & LHe	1	Move dewar to user, x-fer (like Option 4 above)	1. One servicing tank.	1. Transport of large quantities. 2. Sloshing. 3. EVA connecting/disconnecting. 4. Contamination of payload.
	2	Locate LHe dewar at prime user(s) location	1. One servicing tank.	1. Sloshing. 2. EVA connecting/disconnecting. 3. Contamination of payload.
	3	Changeout of small dewars at experiment from depot	1. Smaller quantity. 2. Some robotic activity.	1. Servicing in vicinity of other tanks (venting). 2. Contamination of depot area. 3. Contamination of depot area.
	4	Use small (i.e. 2,000 ltr) dewar "shuttle" fluid req'd	1. One servicing tank.	1. Sloshing. 2. Connecting/disconnecting. 3. Contamination of depot area.

Table 3-16. GRO Experiment Fluid Provisioning Approach Matrix

Experiment Title: 19. GRO				
Description/location: Hydrazine Servicing/Not Attached to Space Station				
Fluids	Opt.	Description	Advantages	Disadvantages
Misc. Fluids	1	Bottle changeout (w/indiv. exp'mts)	1. Smaller quantities of fluids.	1. More operations. 2. EVA/IVA operations more complex. 3. Snag points.
	2	Fluids manifolded (exp'mt moved to depo, refilled, and replaced)	1. Single point of connect/disconnect. 2. EVA centralized.	1. Equipment more susceptible to spills/leaks. 2. Snag points. 3. Contamination of depot area from purging. 4. Movement of bulky experiment to depot area.
	3	Depot plumbed to exp'mts		
	4	Move bottle to user, refill user, rtn. bottle to depot	1. One servicing tank.	1. Sloshing. 2. EVA connecting/disconnecting. 3. Contamination of payload. 4. Snag points.
	5	Flexible line from depot bottle/dewar to the user	1. No transport of fluids in tanks.	1. Equipment more susceptible to spills/leaks. 2. Contamination of depot area from purging. 3. Entanglement of crew with lines. 4. Entanglement of lines with structure.
LHe & LHeI	1	Move dewar to user, x-fer (like Option 4 above)	N/A	
	2	Locate LHe dewar at prime user(s) location		
	3	Changeout of small dewars at experiment from depot		
	4	Use small (i.e. 2,000 ltr) dewar, "shuttle" fluid req'd		

Table 3-17. LDR Experiment Fluid Provisioning Approach Matrix

Experiment Title: 20. LDR				
Description/location: Liquid Helium Servicing/Not Attached to Space Station				
Fluids	Opt.	Description	Advantages	Disadvantages
Misc. Fluids	1	Bottle changeout (w/indiv. exp'mts)	N/A	
	2	Fluids manifolded (exp'mt moved to depo, refilled, and replaced)		
	3	Depot plumbed to exp'mts		
	4	Move bottle to user, refill user, rin. bottle to depot		
	5	Flexible line from depot bottle/dewar to the user		
LHe & LHeI	1	Move dewar to user, x-fer (like Option 4 above)	1. One servicing tank.	1. Transport of large quantities. 2. Sloshing. 3. EVA connecting/disconnecting. 4. Contamination of payload.
	2	Locate LHe dewar at prime user(s) location	1. One servicing tank.	1. Sloshing. 2. EVA connecting/disconnecting. 3. Contamination of payload.
	3	Changeout of small dewars at experiment from depot	1. Smaller quantity. 2. Some robotic activity.	1. Servicing in vicinity of other tanks (venting). 2. Contamination of depot area.
	4	Use small (i.e 2,000 ltr) dewar, "shuttle" fluid req'd	1. One servicing tank.	1. Sloshing. 2. Connecting/disconnecting. 3. Contamination of depot area.

Table 3-18. SBAR Experiment Fluid Provisioning Approach Matrix

Experiment Title: 22. SBAR				
Description/location: Hydrazine and Cold Gas Servicing/Not Attached to Space Station				
Fluids	Opt.	Description	Advantages	Disadvantages
Misc. Fluids	1	Bottle changeout (w/indiv. exp'mts)	1. Smaller quantities of fluids.	1. More operations. 2. EVA/IVA operations more complex.
	2	Fluids manifolded (exp'mt moved to depo, refilled, and replaced)	1. Single point of connect/disconnect. 2. EVA centralized.	1. Equipment more susceptible to spills/leaks. 2. Contamination of depot area from purging. 3. Movement of bulky experiment to depot area.
	3	Depot plumbed to exp'mts		
	4	Move bottle to user, refill user, rtn. bottle to depot	1. One servicing tank.	1. Sloshing. 2. EVA connecting/disconnecting. 3. Contamination of payload.
	5	Flexible line from depot bottle/dewar to the user	1. No transport of fluids in tanks.	1. Equipment more susceptible to spills/leaks. 2. Contamination of depot area from purging. 3. Entanglement of crew with lines. 4. Entanglement of lines with structure.
LHe & LHeI	1	Move dewar to user, x-fer (like Option 4 above)	N/A	
	2	Locate LHe dewar at prime user(s) location		
	3	Changeout of small dewars at experiment from depot		
	4	Use small (i.e. 2 000 ltr) dewar, "shuttle" fluid req'd		

Table 3-19. SIRTF Experiment Fluid Provisioning Approach Matrix

Experiment Title: 24. SIRTF				
Description/location: Liquid Helium Servicing/Not Attached to Space Station				
Fluids	Opt.	Description	Advantages	Disadvantages
Misc. Fluids	1	Bottle changeout (w/indiv. exp'mts)	N/A	
	2	Fluids manifolded (exp'mt moved to depo, refilled, and replaced)		
	3	Depot plumbed to exp'mts		
	4	Move bottle to user, refill user, rtn. bottle to depot		
	5	Flexible line from depot bottle/dewar to the user		
LHe & LHeII	1	Move dewar to user, x-fer (like Option 4 above)	1. One servicing tank.	1. Transport of large quantities. 2. Sloshing. 3. EVA connecting/disconnecting. 4. Contamination of payload.
	2	Locate LHe dewar at prime user(s) location	1. One servicing tank.	1. Sloshing. 2. EVA connecting/disconnecting. 3. Contamination of payload.
	3	Changeout of small dewars at experiment from depot	1. Smaller quantity. 2. Some robotic activity.	1. Servicing in vicinity of other tanks (venting). 2. Contamination of depot area.
	4	Use small (i.e. 2,000 ltr) dewar, "shuttle" fluid req'd	1. One servicing tank.	1. Sloshing. 2. Connecting/disconnecting. 3. Contamination of depot area.

Table 3-20. 3S Experiment Fluid Provisioning Approach Matrix

Experiment Title: 25. 3S				
Description/location: Hydrazine and Cold Gas Servicing/Not Attached to Space Station				
Fluids	Opt.	Description	Advantages	Disadvantages
Misc. Fluids	1	Bottle changeout (w/indiv. exp'mts)	1. Smaller quantities of fluids.	1. More operations. 2. EVA/IVA operations more complex.
	2	Fluids manifolded (exp'mt moved to depo, refilled, and replaced)	1. Single point of connect/disconnect. 2. EVA centralized.	1. Equipment more susceptible to spills/leaks. 2. Contamination of depot area from purging. 3. Movement of bulky experiment to depot area.
	3	Depot plumbed to exp'mts		
	4	Move bottle to user, refill user, rtn. bottle to depot	1. One servicing tank.	1. Sloshing. 2. EVA connecting/disconnecting. 3. Contamination of payload.
	5	Flexible line from depot bottle/dewar to the user	1. No transport of fluids in tanks.	1. Equipment more susceptible to spills/leaks. 2. Contamination of depot area from purging. 3. Entanglement of crew with lines. 4. Entanglement of lines with structure.
LHe & LHeII	1	Move dewar to user, x-fer (like Option 4 above)	N/A	
	2	Locate LHe dewar at prime user(s) location		
	3	Changeout of small dewars at experiment from depot		
	4	Use small (i.e 2,000 ltr) dewar, "shuttle" fluid req'd		

Table 3-21. STO/POP Fluid Provisioning Approach Matrix

Experiment Title: 27. STO/POP		Description/location: Argon, Xenon and Nitrogen Gas Servicing/Not Attached to Space Station		
Fluids	Opt.	Description	Advantages	Disadvantages
Misc. Fluids	1	Bottle changeout (w/indiv. exp'mts)	1. Smaller quantities of fluids.	1. More operations. 2. EVA/IVA operations more complex. 3. Radioactivity
	2	Fluids manifolded (exp'mt moved to depot, refilled, and replaced)	1. Single point of connect/disconnect. 2. EVA centralized.	1. Equipment more susceptible to spills/leaks. 2. Radioactivity 3. Contamination of depot area from purging. 4. Movement of bulky experiment to depot area.
	3	Depot plumbed to exp'mts		
	4	Move bottle to user, refill user, rtn. bottle to depot	1. One servicing tank.	1. Spilling. 2. EVA connecting/disconnecting. 3. Contamination of payload. 4. Radioactivity
	5	Flexible line from depot bottle/dewar to the user	1. No transport of fluids in tanks.	1. Equipment more susceptible to spills/leaks. 2. Contamination of depot area from purging. 3. Entanglement of crew with lines. 4. Entanglement of lines with structure.
LHe & LHeII	1	Move dewar to user, x-fer (like Option 4 above)	N/A	
	2	Locate LHe dewar at prime user(s) location		
	3	Changeout of small dewars at experiment from depot		
	4	Use small (i.e. 2,000 ltr) dewar, "shuttle" fluid req'd		

Note: It is highly unlikely that the Polar Orbiting Platform will be serviced from the SS, but the Table was included for completeness, since the experiment is listed with the SS experiments.

Table 3-22. XGP Experiment Fluid Provisioning Approach Matrix

Experiment Title: 32. XGP		Description/location: Hydrazine Servicing/Not Attached to Space Station		
Fluids	Opt.	Description	Advantages	Disadvantages
Misc. Fluids	1	Bottle changeout (w/indiv. exp'mts)	1. Smaller quantities of fluids.	1. More operations. 2. EVA/IVA operations more complex. 3. RF energy.
	2	Fluids manifolded (exp'mt moved to depot, refilled, and replaced)	1. Single point of connect/disconnect. 2. EVA centralized.	1. Equipment more susceptible to spills/leaks. 2. RF energy. 3. Contamination of depot area from purging. 4. Movement of bulky experiment to depot area.
	3	Depot plumbed to exp'mts		
	4	Move bottle to user, refill user, rtn. bottle to depot	1. One servicing tank.	1. Sloshing. 2. EVA connecting/disconnecting. 3. Contamination of payload. 4. RF energy.
	5	Flexible line from depot bottle/dewar to the user	1. No transport of fluids in tanks.	1. Equipment more susceptible to spills/leaks. 2. Contamination of depot area from purging. 3. Entanglement of crew with lines. 4. Entanglement of lines with structure.
LHe & LHeI	1	Move dewar to user, x-fer (like Option 4 above)	N/A	
	2	Locate LHe dewar at prime user(s) location		
	3	Changeout of small dewars at experiment from depot		
	4	Use small (i.e 2,000 ltr) dewar, "shuttle" fluid req'd		

For the free-flying experiments, it appears the best way to provide hydrazine servicing is to use a fluid interface at the SS, to which a bulk supply of the fluid is attached. If a CSF exists at the growth SS, then the hydrazine fluid interface could be located nearby, and refill the free-flying experiments following other servicing at the CSF. This would keep hydrazine out of the CSF, and reduce the risk of toxic contamination somewhat.

The nitrogen needed for SBAR and 3S could be provided by the INS by the refilling of the empty nitrogen ORUs when the experiment is docked for "other servicing".

3.2.3 EXPERIMENTAL FLUID CARRIER CONCEPTS. The transport and storage of approximately 470,000 liters (150,000 kg) of R & D fluids (Space Station Users) is required to meet growth model requirements from 1994 through the year 2010. The fluid requirements are shown in Table 3-23. The carrier design concepts presented in this section (Section 3.2) are representative of the type of tankage which could satisfy the required range of fluid types/quantities, for a scenario which requires the bulk delivery and storage of fluids (which all of the considered options require in growth configurations).

Preliminary fluid carrier concepts were defined based on liquid and gas containment pressures between 20 and 3000 psia. The basic fluid carrier shown in Figure 3-5 was designed to fit within an envelope of 16 feet in length by 14.5 feet in diameter, and be delivered by the STS to the SS. Preliminary analysis indicated a total launch requirement of 34 fluid carriers through the year 2010, at a rate of 1 to 4 carriers per year for proper time phasing. Approximately 70% of the total fluids carrier volume will be dedicated to liquid helium transport. A liquid helium container volume of 10,000 liters was originally assumed, in conjunction with a quantity of 23 "miscellaneous" (all other fluids needed for US and international R & D) fluid carriers.

The concept shown in Figure 3-5 is of limited practical value and versatility because it is a "double-wide" type of unpressurized cargo container. It is the length of an unpressurized cargo container (sixteen feet) as defined in Reference 2-2 rather than the eight foot length of a fluids carrier. Hence the term "double-wide".

A more modular conceptual design, such as the Miscellaneous Fluids Carrier shown in Figure 3-6 enables the delivered fluid quantity to be more closely tailored to the requirements. This led to the idea of having a separate container for liquid helium only. Since the volume of the liquid helium required is significantly greater than the rest of the fluids combined, a dedicated helium carrier concept was defined. This configuration is shown in Figure 3-7.

This drawing concept shows the STS trunion attachments and the diameter of the carrier which was selected to be compatible with the STS Orbiter Payload bay. The primary structural support

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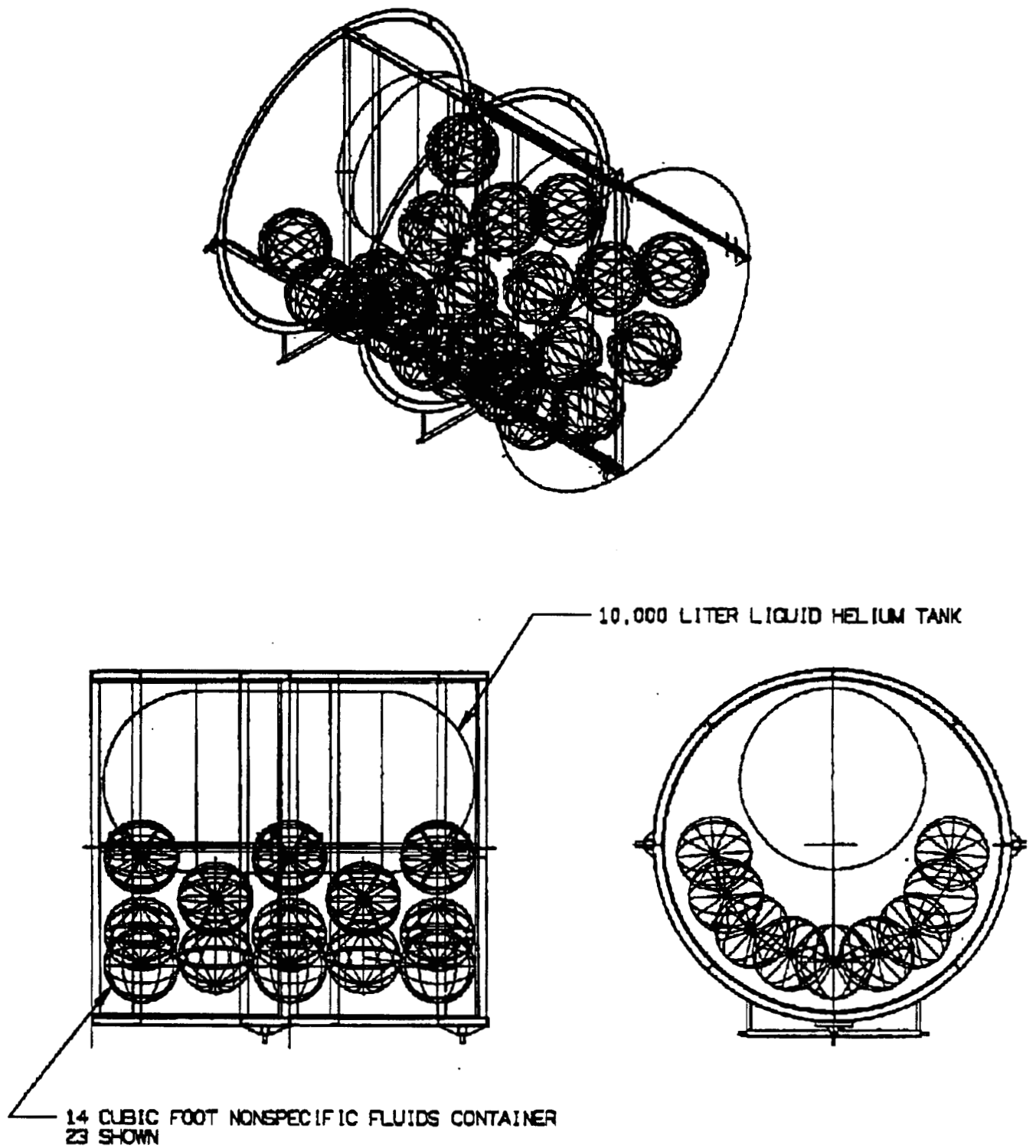


Figure 3-5. CAD Concept of a Fluids Carrier for STS Delivery to the Space Station

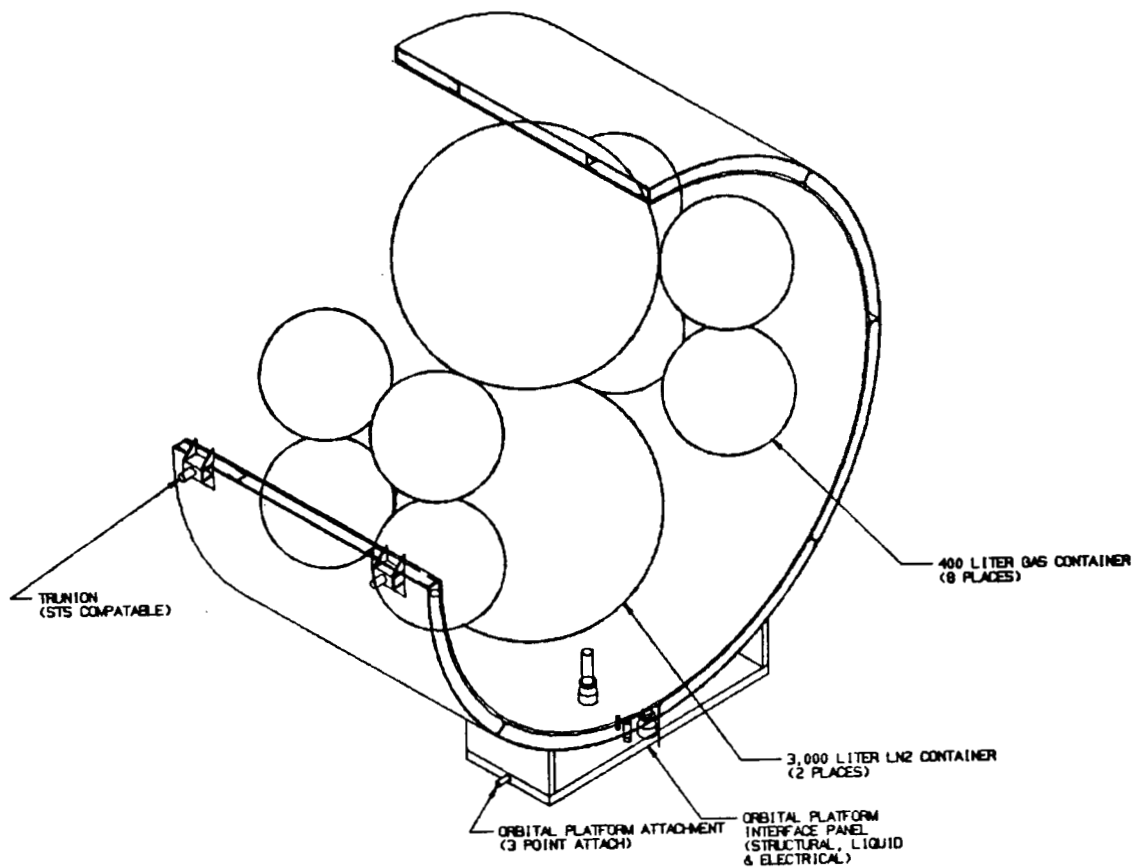


Figure 3-6. Miscellaneous Fluids Carrier

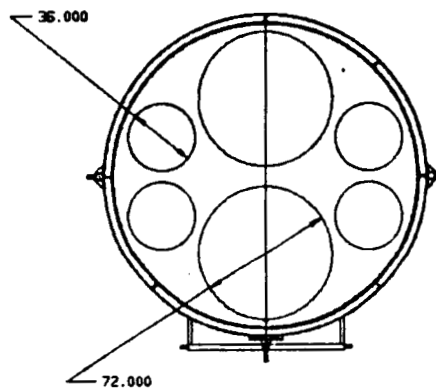
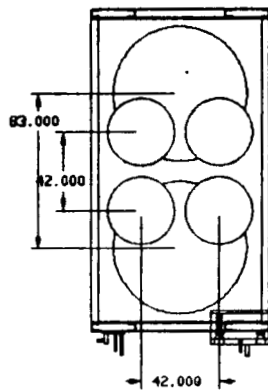
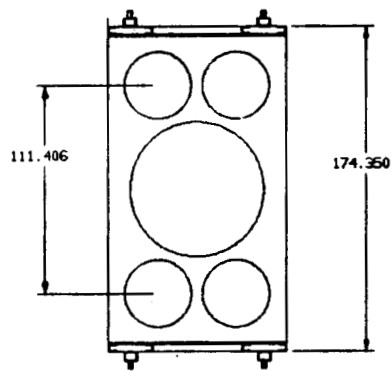


Figure 3-6. Miscellaneous Fluids Carrier (continued)

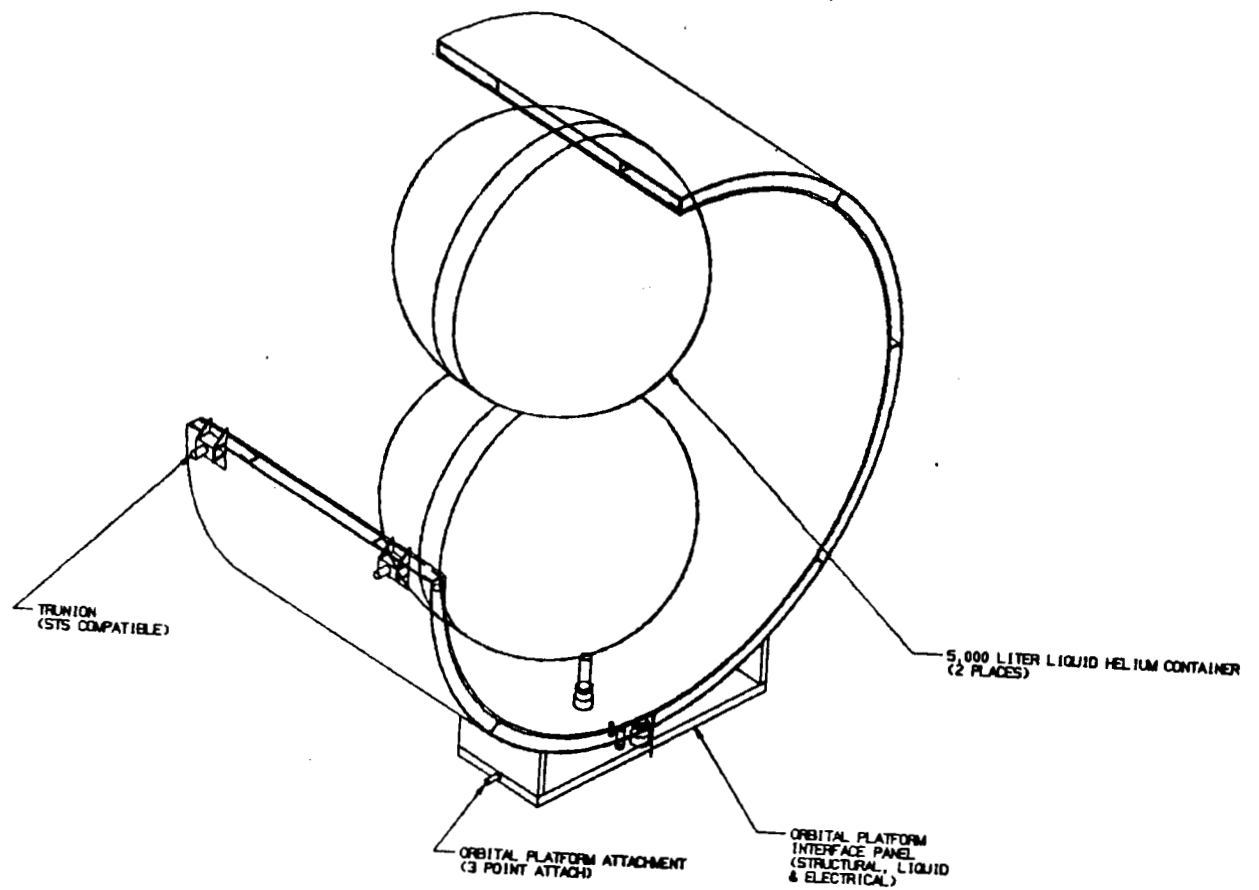


Figure 3-7. Dedicated Liquid Helium Carrier

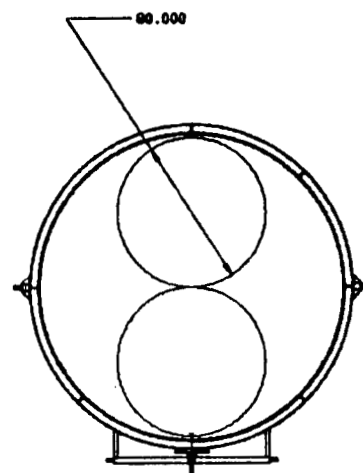
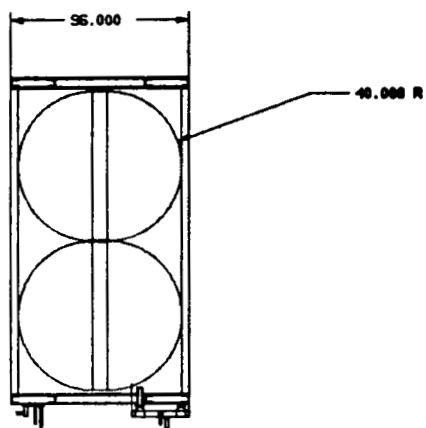
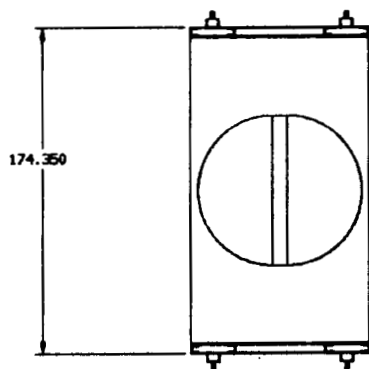


Figure 3-7. Dedicated Liquid Helium Carrier (continued)

constructed of 6061 aluminum alloy and consists of radial ring frames, longitudinal stringers and a skin. The rectangular panel shown at the base contains the three point orbital platform attachment developed for the Long Term Cryogenic Storage Facility (LTCSF), fill, drain and vent valves as required, TV camera target for remote manipulation, alignment pins, electrical interfaces and any other required devices. Although the tanks would be mounted most likely with low thermally conductive struts, electrical continuity would have to be maintained at the same level throughout the structure and tanks.

A dedicated hydrazine carrier consisting of three tanks with a volume of 2,000 liters each, was configured as shown in Figure 3-8. It is expedient from both safety and operational viewpoints to maintain a separate hydrazine carrier. The tanks could be supported within the carrier in a number of ways; struts attached to fittings on the tanks allowing for differential thermal expansion and contraction and/or pressure changes, partial foam encapsulation, or perhaps latches to permit remote manipulator arm insertion and removal of the tanks. Section 4 includes a drawing of the carriers with the IOC and growth SSs, and includes a "representative" tank support method.

Nitrogen, Argon, Methane, Xenon and "rare" gas fluid requirements are satisfied by the Miscellaneous Fluids Carrier. This carrier consists of two liquid nitrogen spherical containers each with a capacity of 3,000 liters, and eight high pressure gas containers, each with a capacity of 400 liters. These gases include This carrier design is shown in Figure 3-6.

The requirements for the gases (other than the nitrogen liquid) are so low that three foot diameter containers were selected for commonality and ease of handling and storage, and delivered volume of each is more than sufficient to provide the necessary fluids on orbit during a particular time period.

3.3 CRYOGENIC PROPELLANT PROVISIONING

The cryogenic LH2/LO2 propellant storage systems developed under NASA-MSFC's "Long Term Cryogenic Storage Facility System Study" (Reference 1-2, -3, -4, and -5) were used as baseline LO2/LH2 propellant storage concepts for this study, and were designed to the groundrules defined by NASA-MSFC.

Appropriate combinations of the LTCSFSS propellant storage tanksets allowed for several co-orbiting platform concepts to be designed, each tailored to a particular Code Z mission model, as well a concept for the STV mission model.

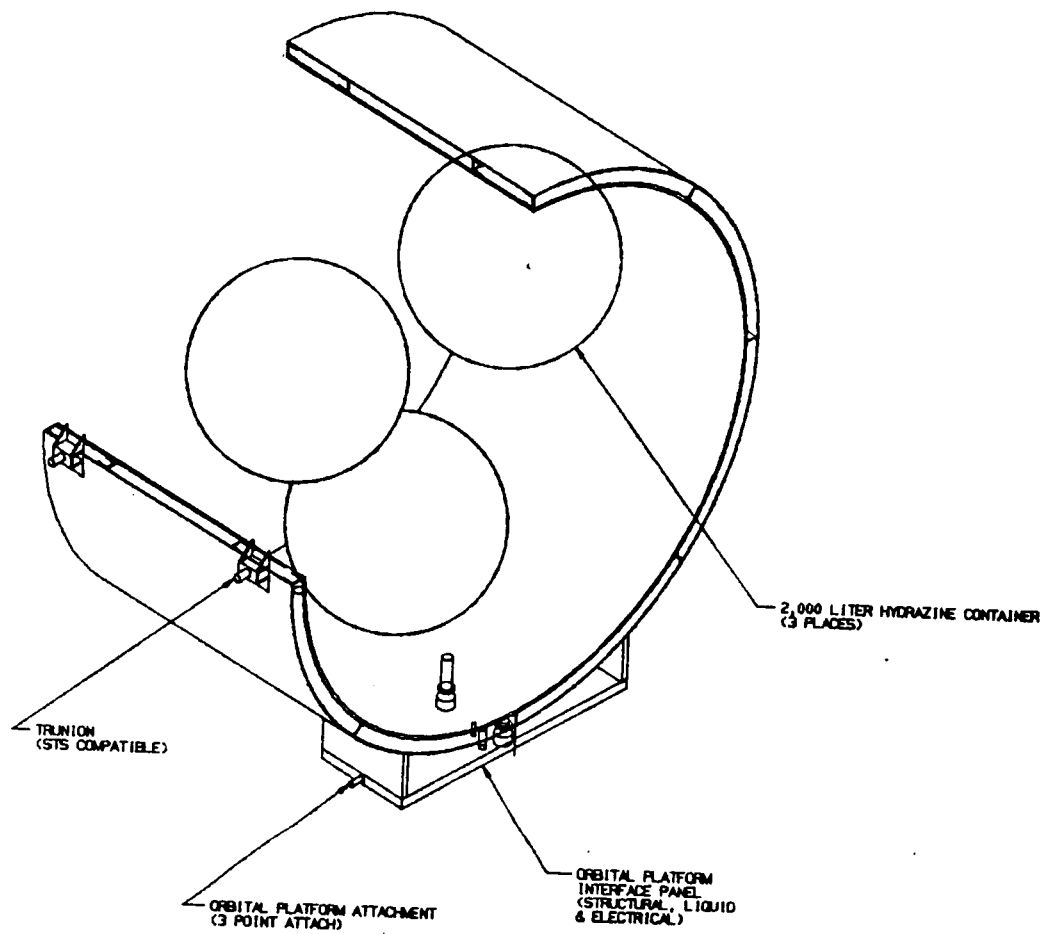


Figure 3-8. Dedicated Hydrazine Fluid Carrier

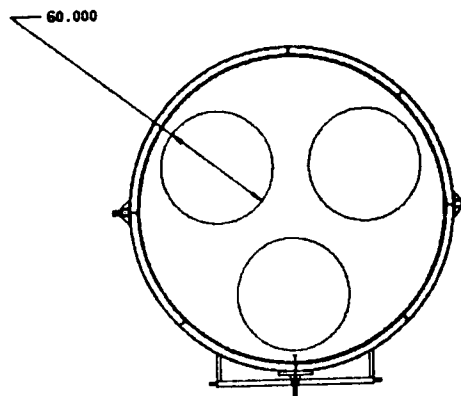
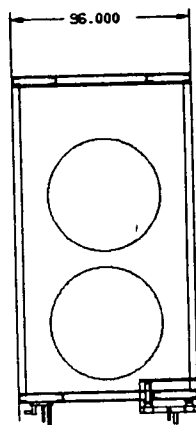
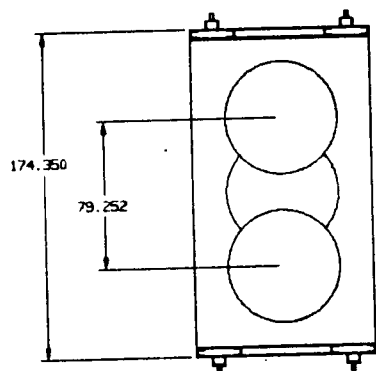


Figure 3-8. Dedicated Hydrazine Fluid Carrier (continued)

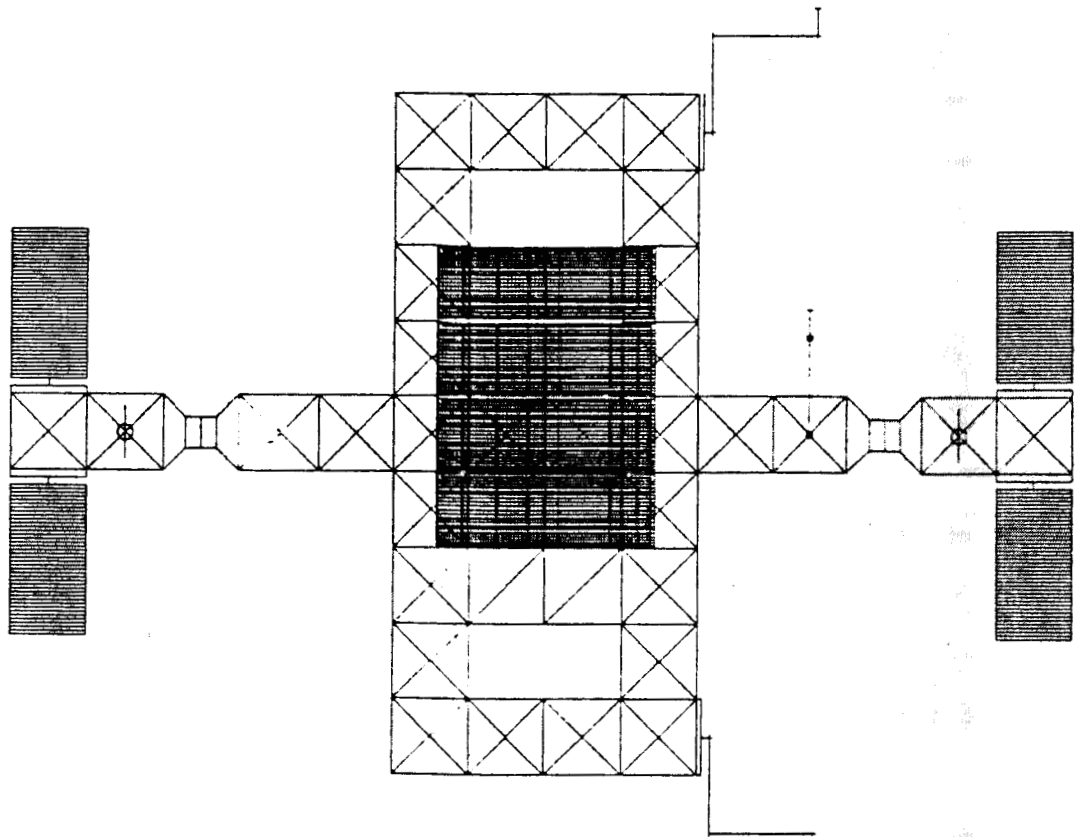
In addition, detailed thermodynamic processes which effect LTCSFSS tankset performance were analyzed with GDSS depot design computer codes to support the transfer operation definitions/timelines reported in Section 4.

3.3.1 PROPELLANT TANKS ON CO-ORBITING PLATFORMS. A family of tankset types, sizes, and accompanying platforms were designed during 1988 under the LTCSFSS contract to meet a variety of launch vehicles, mission model propellant needs, and delivery scenarios. The development of these concepts and corresponding results are detailed in Reference 1-3. Figures 3-9 through 3-14 contain refueling platform concepts to support the cryogenic (and also a limited quantity of Argon and Hydrazine) propellant requirements defined in Section 2 for STV and Code Z Mission Models. The size/fluid capacity of each concept is based on fluid requirements (with a design margin of safety) for the particular mission model. STV concepts -a and -b illustrate platform flexibility.

3.3.2 PROPELLANT TANKS ATTACHED TO SPACE STATION. Propellant provisioning for the STV (and possibly the Lunar missions) by LH2/LO2 storage at the SS was considered. The STV mission model provided the propellant requirements for this concept, as well as LTCSFSS tanksets. Both microgravity and reboost settling liquid acquisition methods were considered to assess their impact on Space Station and transfer operations.

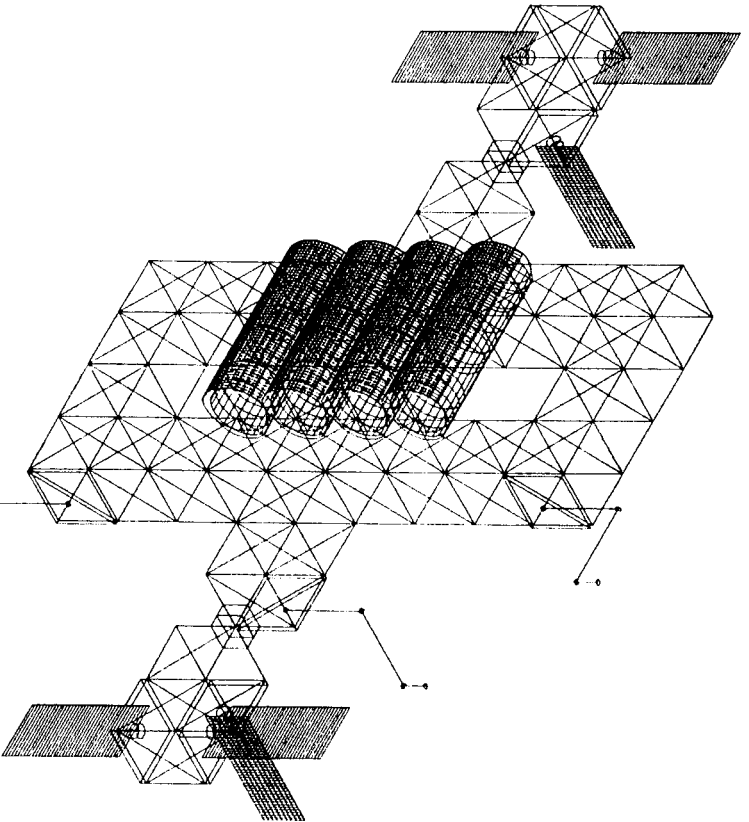
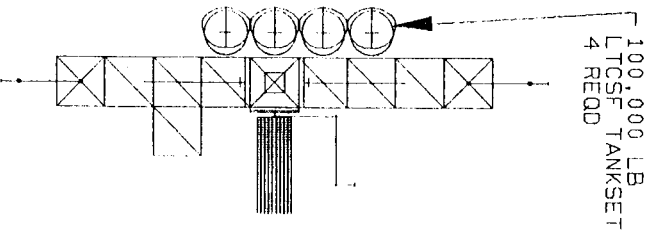
3.3.3 PROPELLANT TANKAGE TRANSFER AND STORAGE PERFORMANCE. Regardless of LTCSFSS type tankage location, it is important to quantify the thermal performance; both the steady-state boiloff performance during quiescent storage periods, as well as pressurant required and pressure/temperature histories in user tanks during transfer of fluids. The fluid transfer and storage performance for liquid hydrogen and liquid oxygen tanksets were investigated. Two depot sizes were considered, 100,000 lbm and 200,000 lbm. Both tank sets are wet-launched with an oxygen-to-hydrogen mass ratio of 6:1. The propellant tanks are cylindrical with elliptical end caps. The Tank Geometry module of the COOLANT program (Reference 1-5) was used to determine the relevant sizes and masses for these tank sets, which are summarized in Table 3-24.

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ORBITAL DEPOT FOR STV

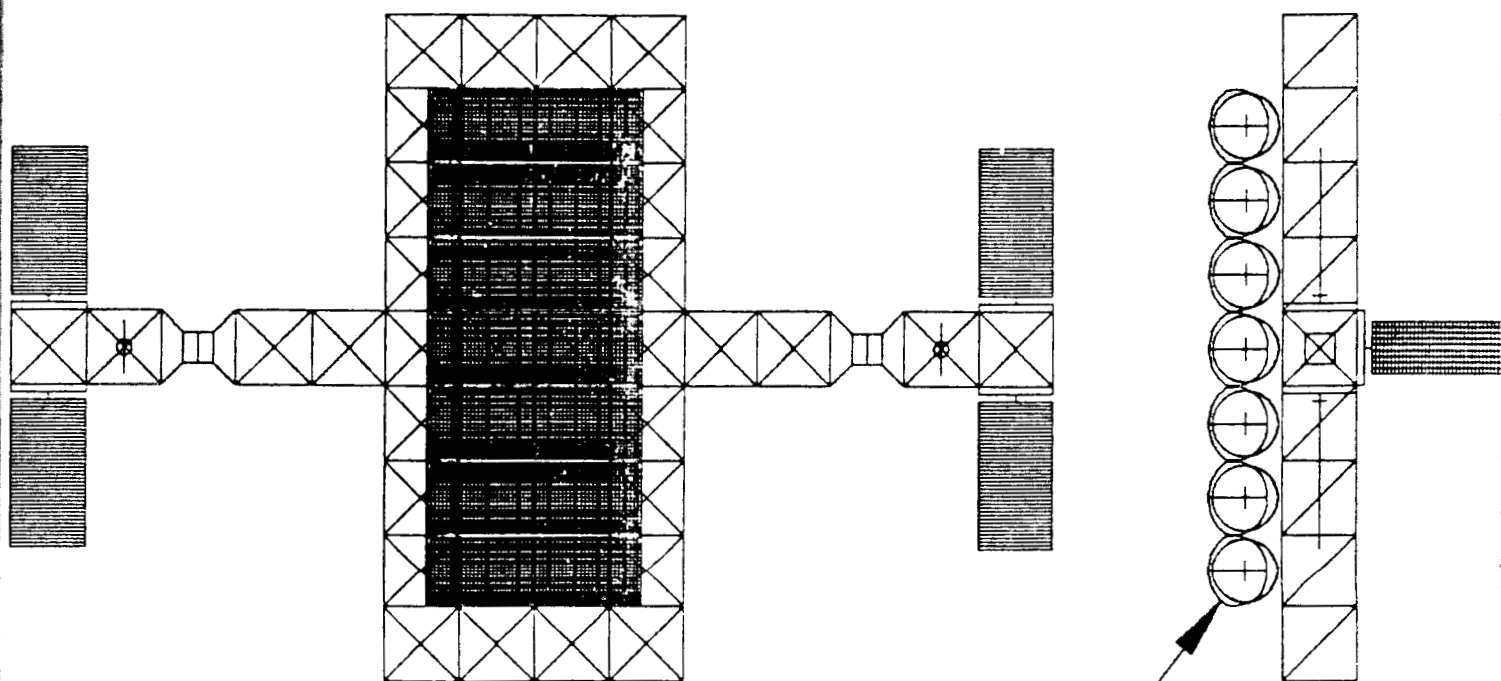
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Figure 3-9.

Orbital Depot for STV -a

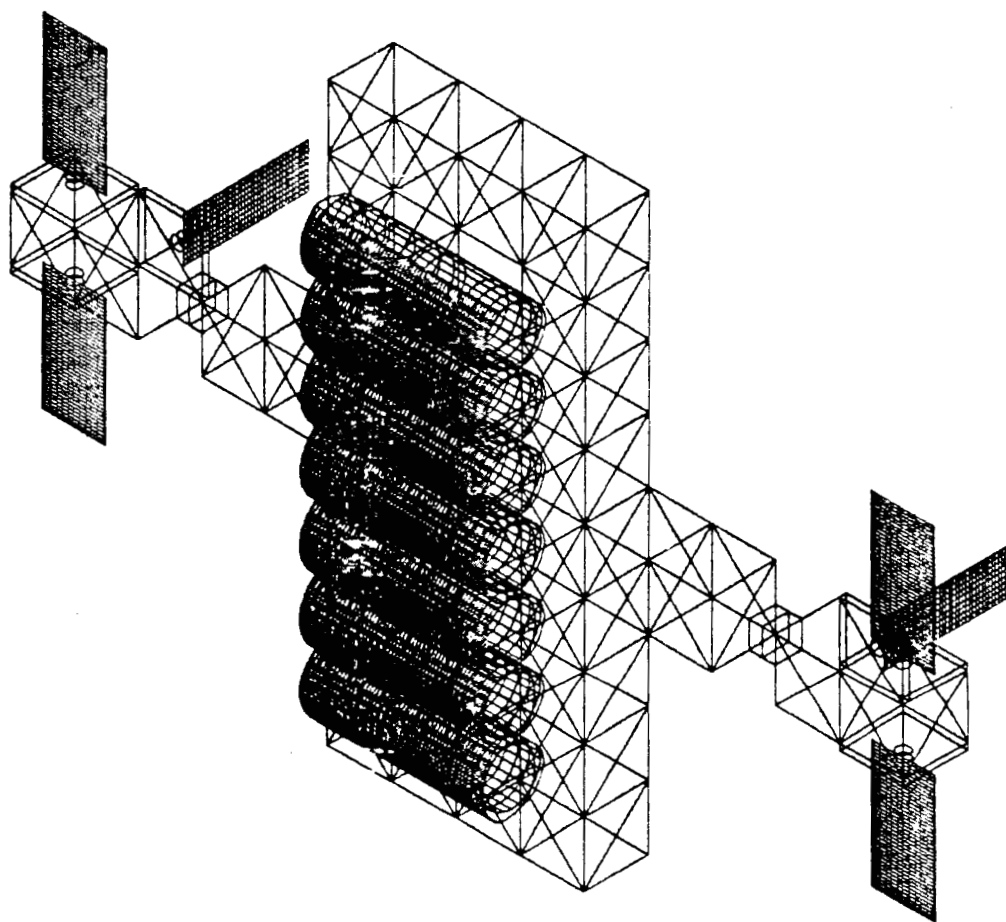


TANKSET,
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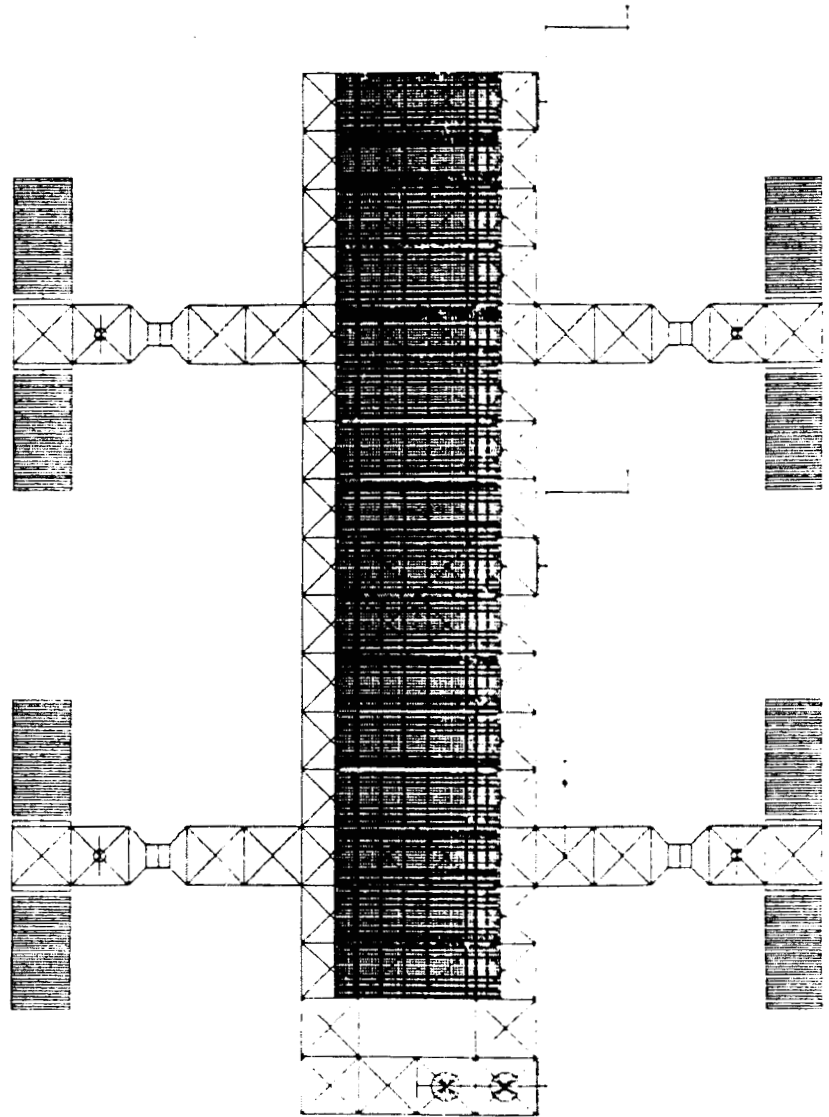
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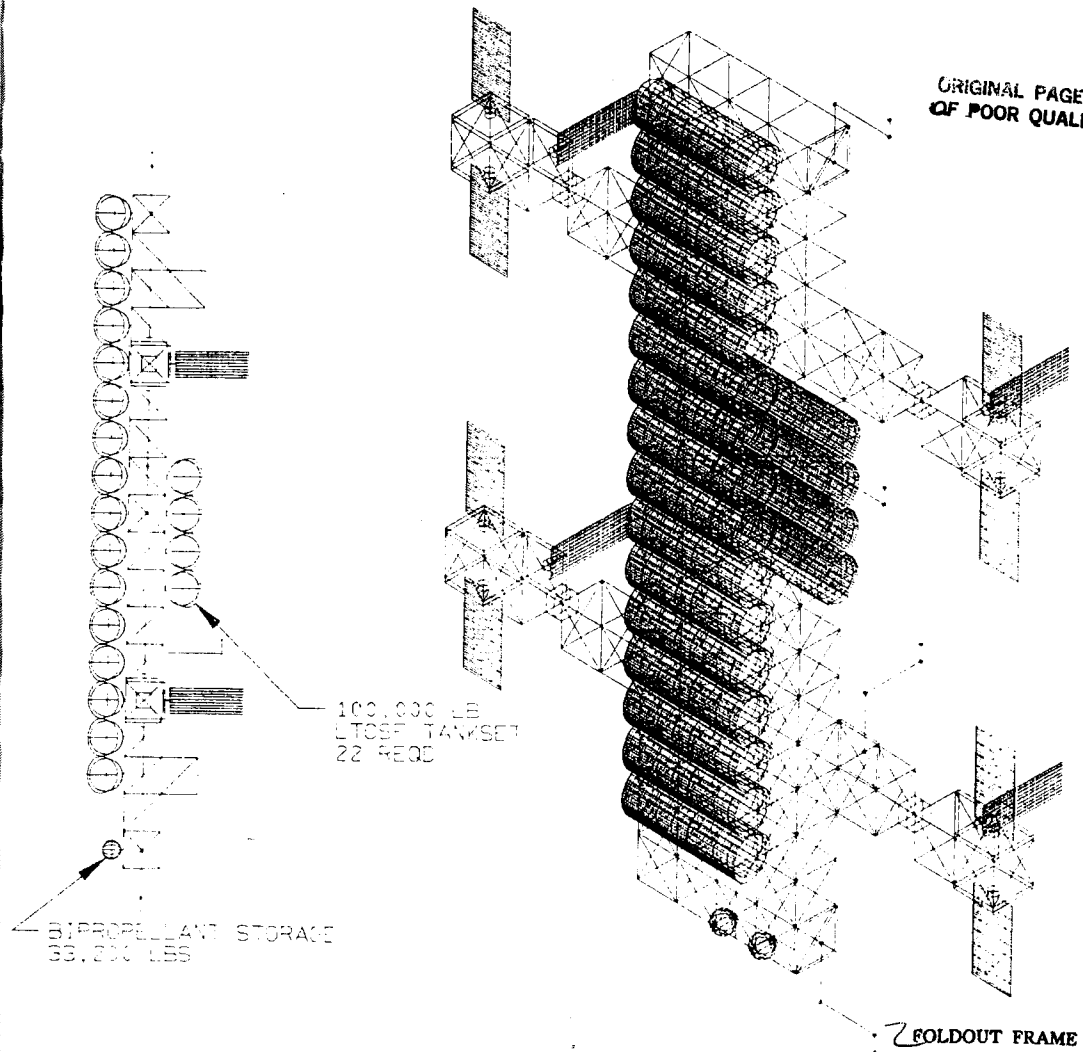
Figure 3-10. Orbital Depot for STV -b



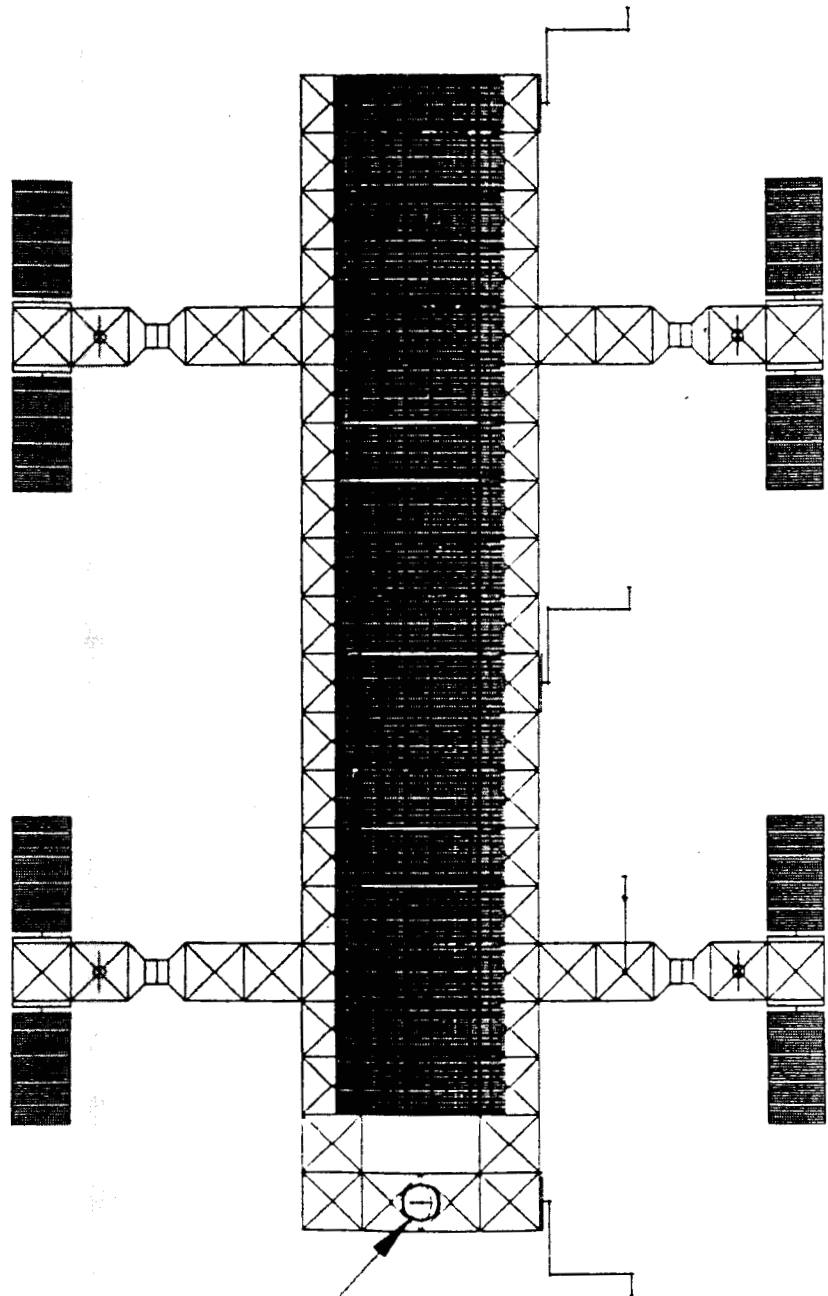
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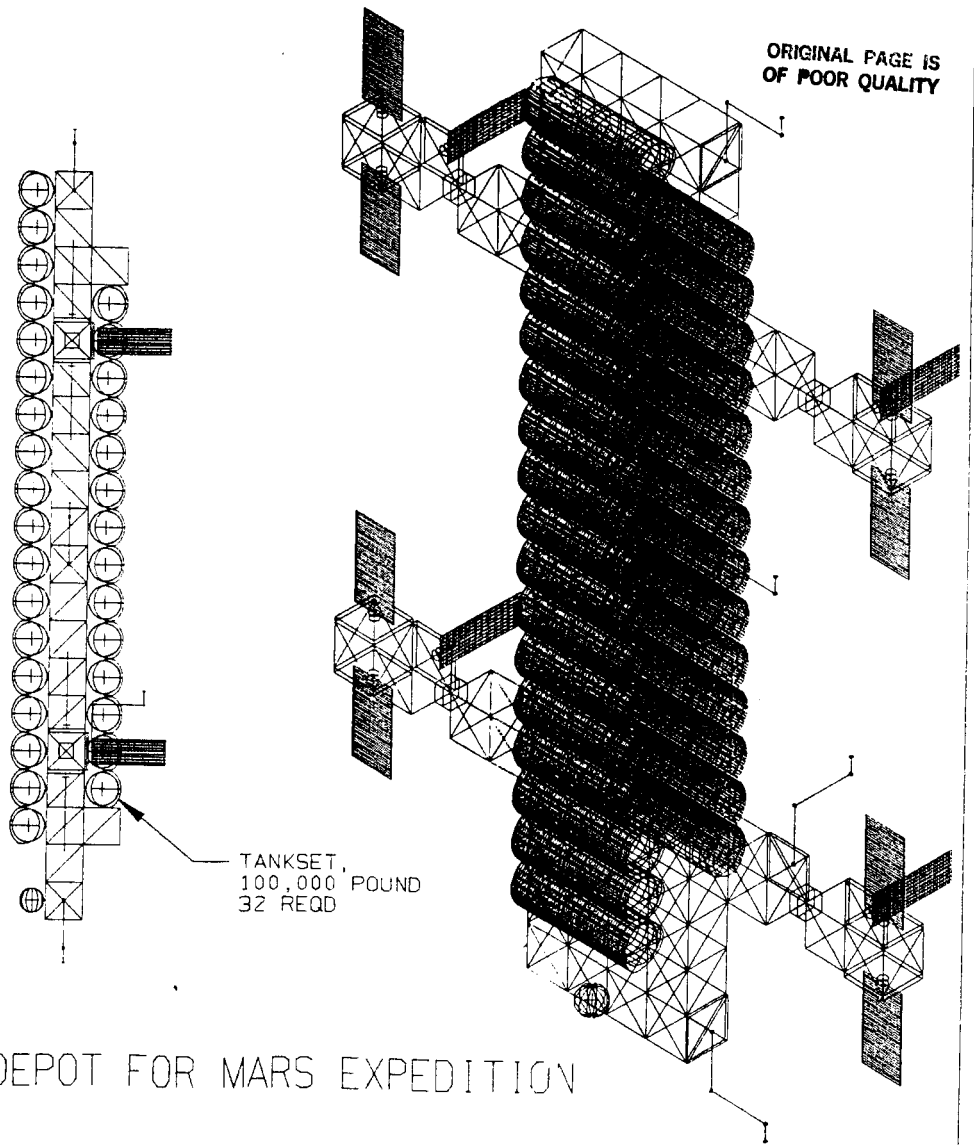
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HYDRAZINE
31.000 LBS

ORBITA

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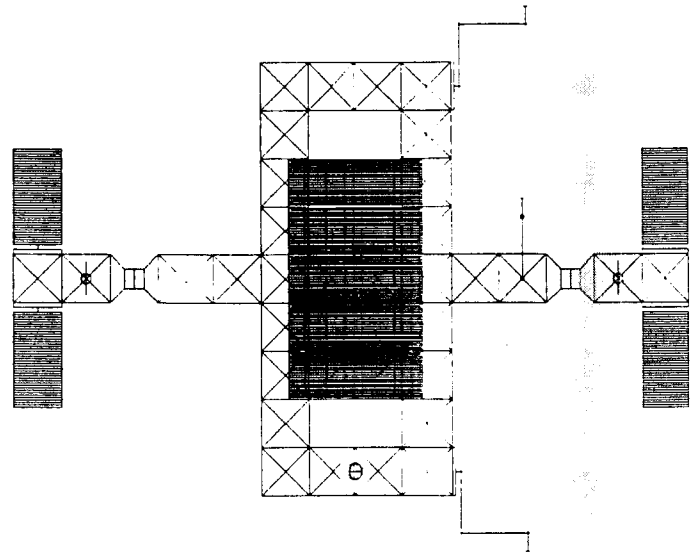


DEPOT FOR MARS EXPEDITION

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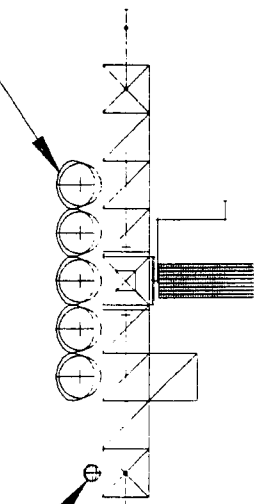
Figure 3-12. Orbital Depot for Mars Expedition



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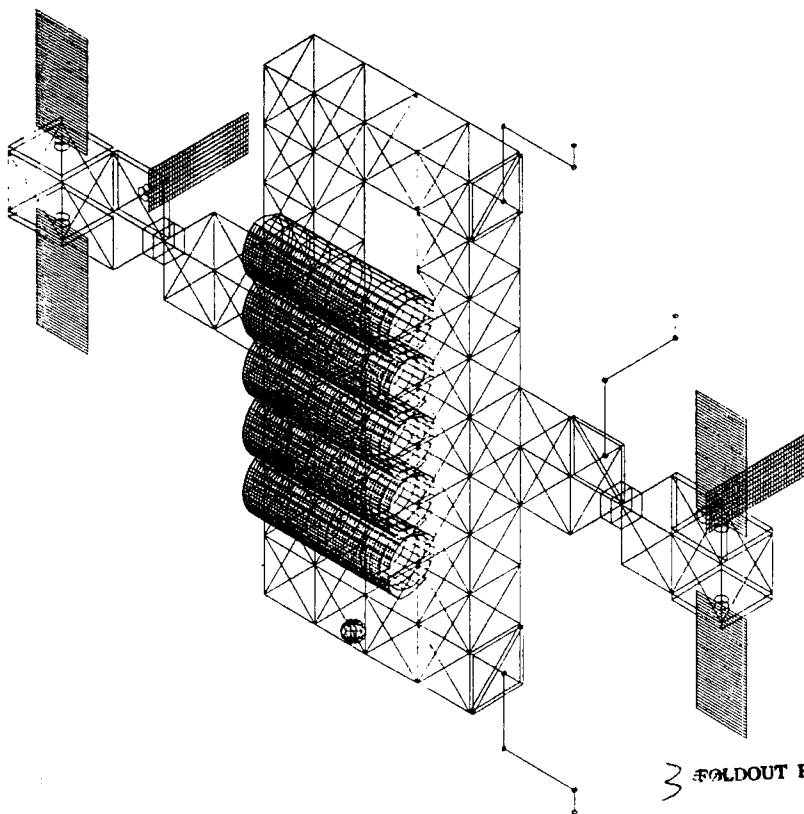
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100,000 LB LTCSF TANKSET
4 REQD PLUS 1 FOR CONTINGENCY



5,000 LBS STORABLES

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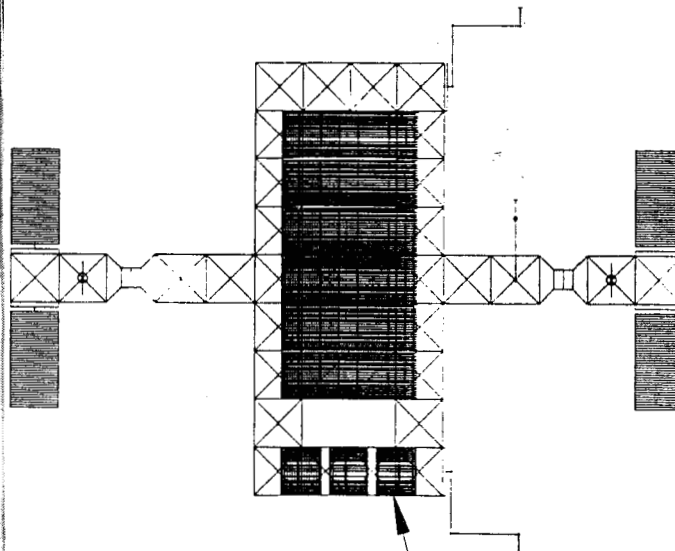
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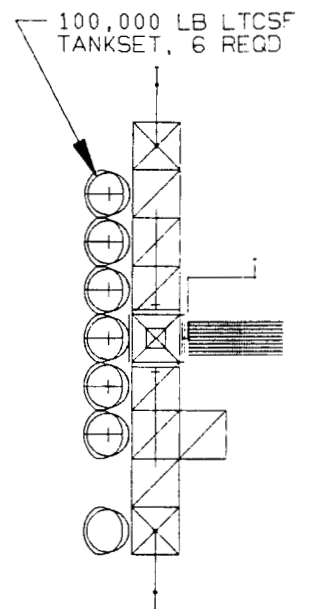
ORBITAL DEPOT FOR LUNAR OBSERVATORIES

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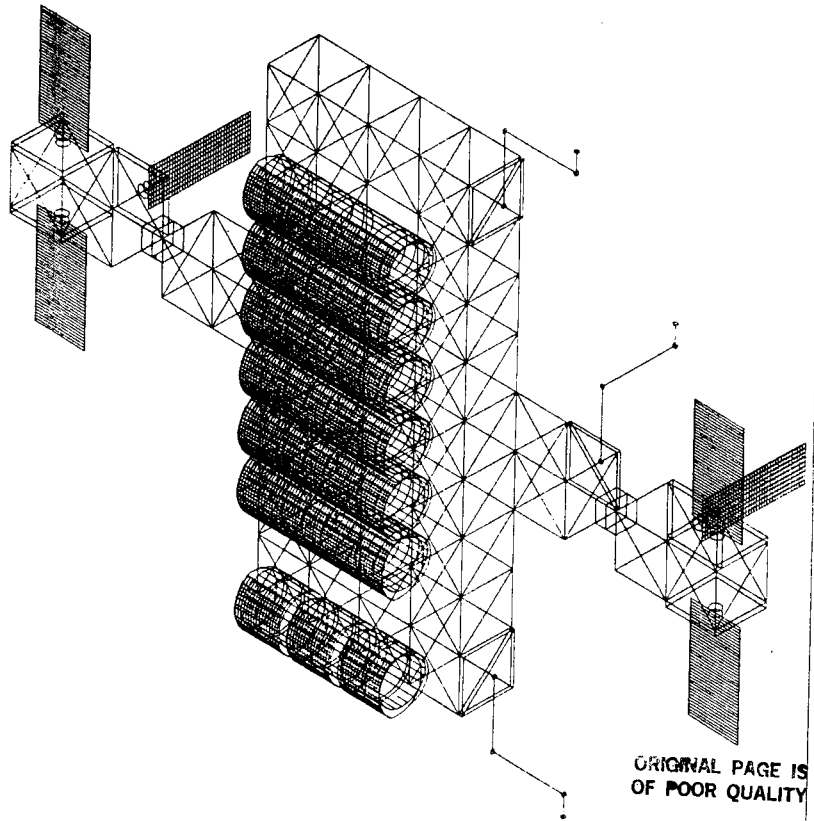


LIQUID ARGON
3 CONTAINERS
270,000 LBS



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ORBITAL DEPOT FOR LUNAR BASE TO MARS

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Table 3-24. Geometry and Analytical Parametric Data for COOLANT Program

Tank Set	100klb		200klb	
<i>Fluid</i>	<i>Hydrogen</i>	<i>Oxygen</i>	<i>Hydrogen</i>	<i>Oxygen</i>
Diameter (in)	154	154	200	200
Cylinder Length (in)	247	42.16	284.5	41.6
Elliptical End Cap Radius Ratio	1.379	1.379	1.379	1.379
Tank Volume (ft3)	3465	1257	6930	2514
Tank Wall Area (ft2)	1256	567.3	1959	899.5
Supported Mass (lbm)	21,484	90,009	40,145	178,305
Thermal Mass (lbm)	5141	3201	7614	5353

Propellant Boil Off Rates

The System Performance module of the COOLANT program was used to investigate the steady state boil off rates for these two tank sets. The boil off rate is strongly dependent on the tank insulation and VCS (Vapor Cooled Shield) configuration. Four one-inch thick MLI (Multilayer Insulation) blankets were used on each tank. The hydrogen tanks used a two-pass, parallel flow VCS, with the inner and outer shields located at 30 and 66 percent of the distance from the tank wall to the outer MLI layer. The oxygen tanks used a single pass hydrogen shield located at 74 percent of the distance from the tank wall to the outer MLI layer. The boil off rates are also dependent on the source temperature. The environment associated with various source temperatures are given in Table 3-25.

Table 3-25. Environment Source Temperatures for Propellant Storage Tanksets

Source Temp. (R):	457	459	364	332
Environment:	LEO	Lunar Based	Mars Orbit	Mars Orbit
		(on surface)	(end Mars-pointed)	(end Sun-pointed)

The steady state boil off rates for a range of source temperatures between 300 and 490 R are shown in Figure 3-15. The boil off rates for the 200klb tank set are higher than the 100klb tank set, by a factor of ~1.6 for hydrogen and ~1.8 for oxygen. This is due to the larger surface areas exposed to space for the larger tankset size. However, when normalized by the tank capacity, the boil off rates for the 200klb tank set are lower than the 100klb tank set by ~20 percent for hydrogen and ~10 percent for

oxygen, as shown in Figure 3-16 (the ratio of surface area to stored volume is lower for the larger tankset size). The combined hydrogen and oxygen boil off rates, normalized by the total tank set capacity, are shown in Figure 3-17. The normalized combined boil off rate for the 200klb tank set is ~10 percent lower than the 100klb tank set. In the LEO environment (457 R), the combined boil off rate is 0.24% per month for the 200klb tank set and 0.26% per month for the 100klb tank set. To calculate the steady state boil off rates the tank pressure was assumed constant at 22 psia. The TVS (Thermodynamic Vent System) minimum operating pressure was 7 psia.

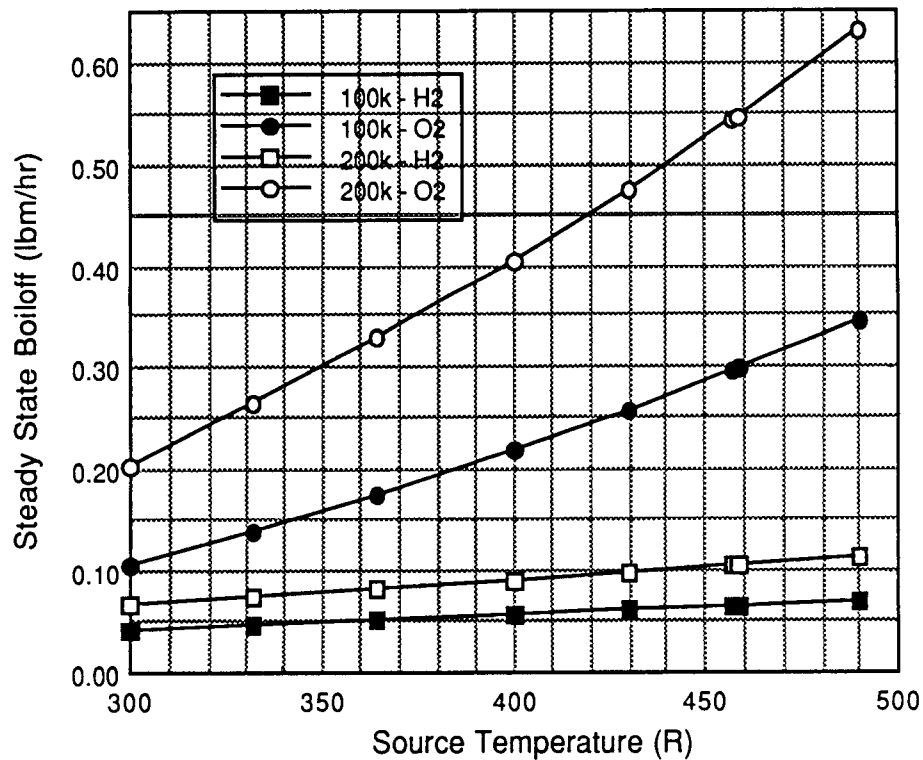


Figure 3-15. Steady-state Boiloff in lbm/hr for a Range of Source Temperatures.

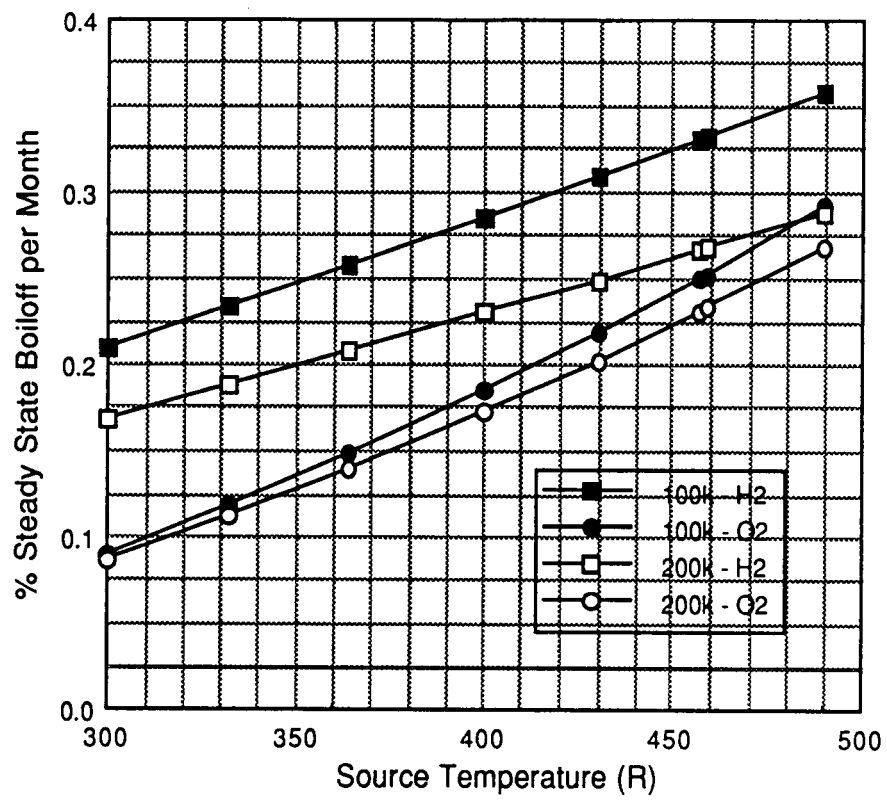


Figure 3-16. Steady-state Boiloff Normalized by Tank Capacity.

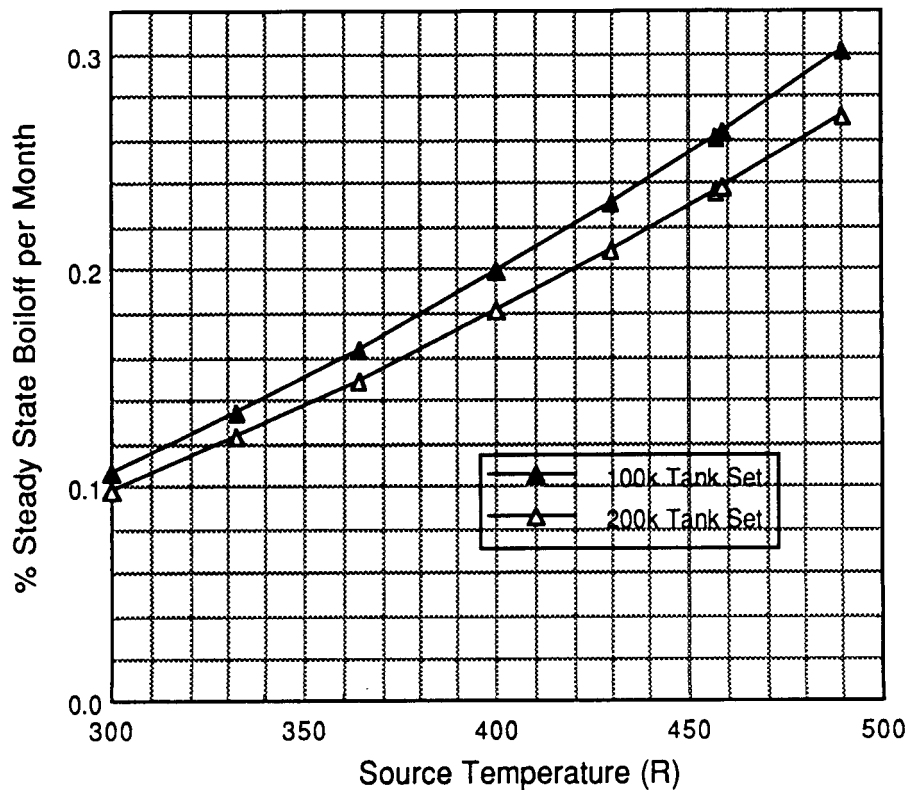


Figure 3-17. Combined Steady-State Boiloff.

Typically the tanks will be sealed and the pressure will rise to a set maximum, at which time the TVS vent valve will be opened to lower the tank pressure back to a preset minimum, completing the cycle. For a typical system, the TVS valve opens when the tank pressure reaches 20.5 psia, and turns off when the tank pressure falls to 19.5 psia. The TVS flow rate, when operating, may be substantially higher than the steady state value. To accommodate this larger mass flow rate, and also provide the capability of conditioning of stored propellants from a given storage pressure to a lower storage pressure (defined by system/user pressure requirements), the TVS must be oversized substantially.

For example, assuming a source temperature of 457 R, the cycle time is 826 hrs for the 100klb hydrogen tank and 1037 hrs for the 200 klb. hydrogen tank, which requires that the TVS operate about 22 percent of the time for both the 100 and 200 klb. tank sizes. The boiloff rates associated with these duty cycles are 2.2 times higher than the corresponding steady state boil off rates presented earlier.

A passive TVS is used to maintain the tank pressure within acceptable limits. The TVS is assumed to be wall-mounted to take advantage of the tank wall as an extended heat transfer surface. The GDSS WALLTVS program was used to calculate the tube length necessary to completely vaporize the fluid in the line and the total pressure drop through the line, the results of which are shown in Table 3-26.

Table 3-26. TVS Sizing Analyses Results

Steady State Boil Off:

<i>Tank</i>	<i>Length (ft)</i>	<i>Pressure Drop (psi)</i>
100klb - H2	24	0.0005
200klb - H2	30	0.0011
100klb - O2	31	0.0047
200klb - O2	38	0.011

Oversized TVS (required for practical system design):

100klb - H2	75	0.079
200klb - H2	103	0.22
100klb - O2	72	0.44
200klb - O2	97	1.5

Note: The TVS is assumed to be wall-mounted

For all the above cases a source temperature of 457 R and a gravity level of $32.2 \times 10^{-5} \text{ ft/sec}^2$ was assumed. Longer TVS tubes are necessary for the oversized cases because the TVS flow rates are higher due to the intermittent operation and extended capability.

Pressurant Requirements

Liquid hydrogen will be transferred by pressurizing the tank with hydrogen vapor to provide the

required NPSP (net positive suction pressure) for the transfer pump(s). The mass of pressurant required is dependent on a number of parameters, including the mass of liquid transferred, initial tank pressure, transfer pressure, tank volume, pressurant temperature, and the initial amount of ullage in the tank. GDSS's PRSTHRM program was used to analyze the pressurant requirements for transfers of liquid hydrogen. A representative transfer will be to an STV with a total propellant capacity of 52,500 lbm. Assuming a 6:1 oxygen-to-hydrogen mass ratio, a total of 7500 lbm of liquid hydrogen will be transferred. The initial tank pressure and transfer pressure considered were 20 and 25 psia, respectively.

Figures 3-18 and 3-19 show the mass of pressurant required to complete a transfer for a range of initial ullage fractions. These figures include results for both the 100klb and 200klb hydrogen tanks at two pressurant temperatures, 45 and 70 R. Note that 45 R is only five degrees higher than the saturation temperature at the transfer pressure of 25 psia. To predict the mass of pressurant necessary to complete a transfer, the collapse factor must be known (the collapse factor effects the rate at which the injected pressurant gas exchanges heat with and condenses into the supply tank saturated liquid). The "worst case" would be a total collapse of the pressurant vapor which would require the most pressurant mass to complete the transfer. This case does not depend on the temperature of the pressurant. The "best case" would be if no pressurant collapsed, and would require the least amount of pressurant to complete the transfer. The actual case lies between these two extremes and was predicted using the Moore correlation. The mass of pressurant required increases as the ullage fraction increases. However, the most dramatic increase is associated with a decrease in the pressurant temperature.

Prechill

A tank must be prechilled to a "target temperature" to allow it to be filled without venting. The prechill consists of a number of charge, hold, and vent cycles with cold liquid, which removes sensible heat from the tank wall/cold mass. The GDNVF program was used to predict the amount of liquid hydrogen necessary to prechill the 100klb hydrogen and 200klb hydrogen tanks from an initial temperature of 457 R to a temperature of 100 R. The mass injected during each charge cycle was defined by the amount necessary to cause the tank pressure to rise to about 40 psia, if allowed to come to equilibrium. The liquid "charge" was held until the rate of decrease in the tank wall temperature was less than a prescribed value (the rate of change asymptotically approaches zero with time). This value was varied to allow the prechill to occur in less than eight hours. The charge cycle was followed by a vent to an intermediate tank pressure which maximized the amount of energy the ullage could receive from the tank wall. The remaining charge was again held until the rate of decrease in the tank wall

temperature was less than the prescribed value, at which time the tank was fully vented and recharged. The injected liquid hydrogen was supplied at 36.6 R.

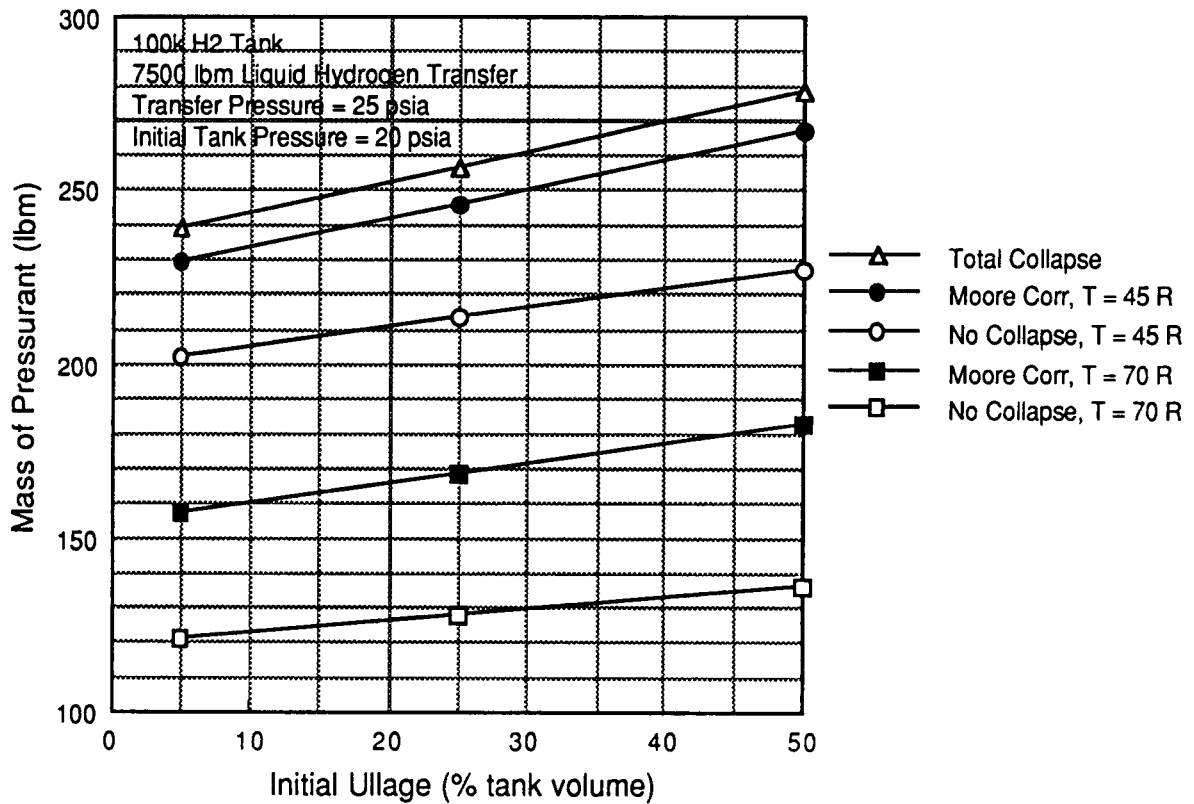


Figure 3-18. Required Pressurant, 7500 lbm Transfer of LH2 from a 100 klb. Tank Set

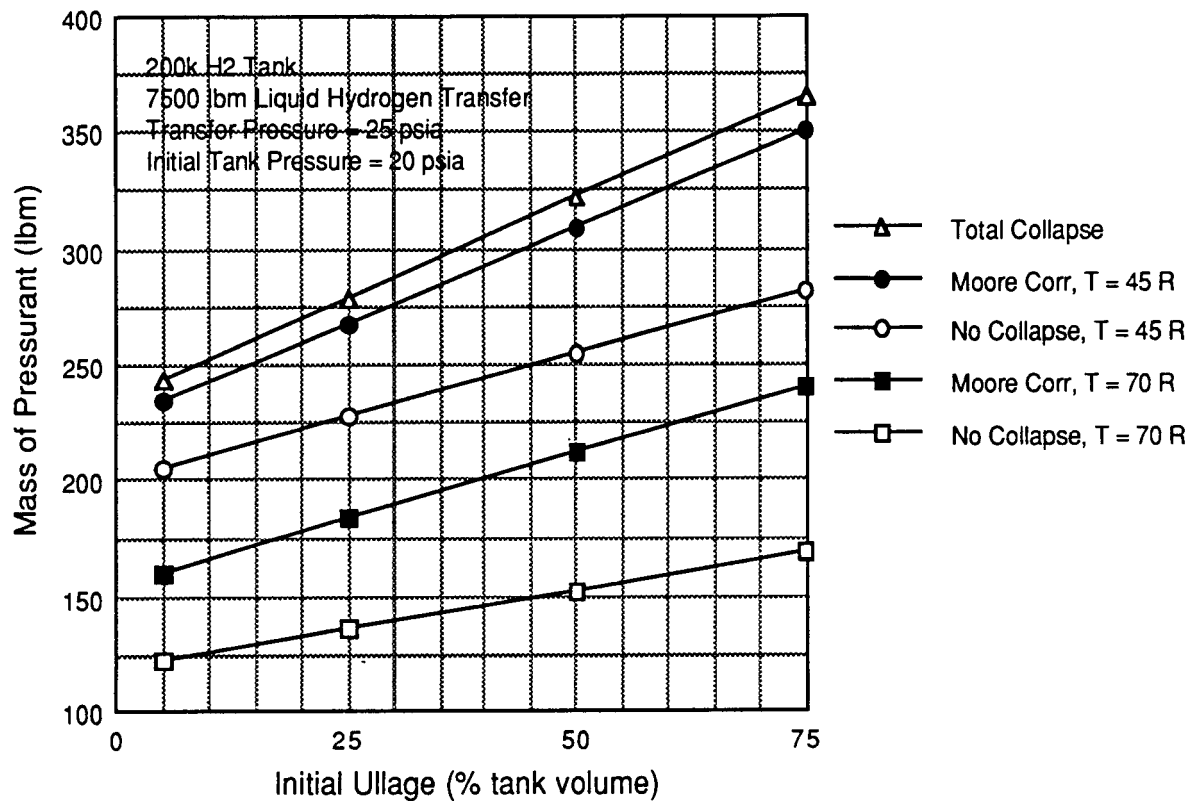


Figure 3-19. Required Pressurant, 7500 lbm Transfer of LH2 from a 200 klb. Tank Set

Profiles of the tank pressure, wall temperature, and mass supplied are shown in Figures 3-20 through 3-22 for the 100klb hydrogen tank and in Figures 3-23 through 3-25 for the 200klb hydrogen tank. To chill the 100klb hydrogen tank down to 100 R in 7.9 hours required 553 lbm of liquid hydrogen. The 200klb hydrogen tank required 842 lbm of liquid hydrogen to prechill in 7.3 hours. The profile of the tank wall temperature indicates that little additional cooling would be obtained from more than two vents for each charge.

It is possible to prechill the tanks more rapidly than the times indicated, but this will result in a larger total injected mass requirement, due to the fact that insufficient time is allowed for the injected fluid to absorb sensible heat from the tank wall/cold mass.

Several prechill cases for the LO2 tank were analyzed. Initially, the cooldown was done in a manner similar to that used for LH2. A charge, hold, vent process was used, and results indicate that the

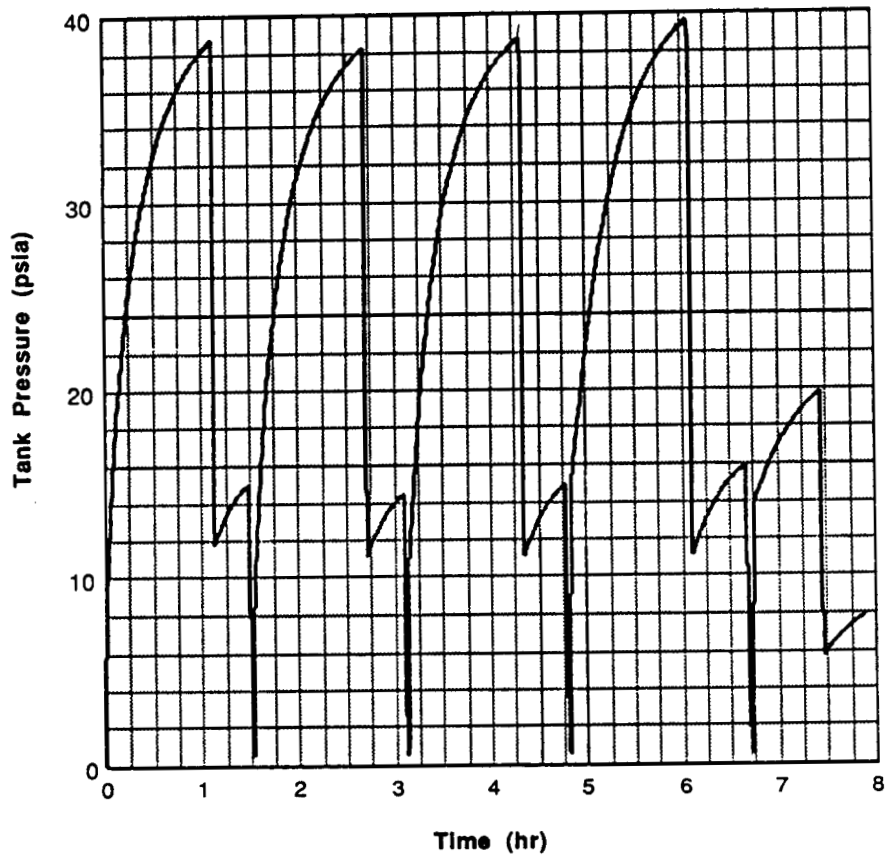


Figure 3-20. Tank Pressure History During Prechill of a 100 Klb. LH2 Tank Set

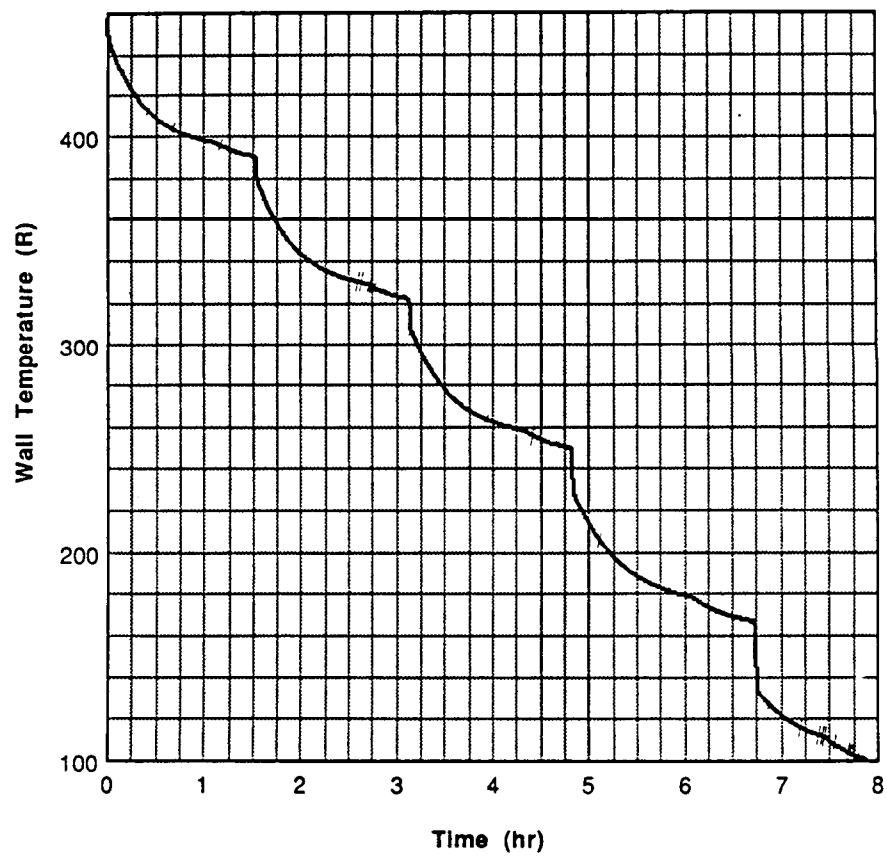


Figure 3-21. Tank Wall Temperature History During Prechill of a 100 Klb. LH2 Tank Set

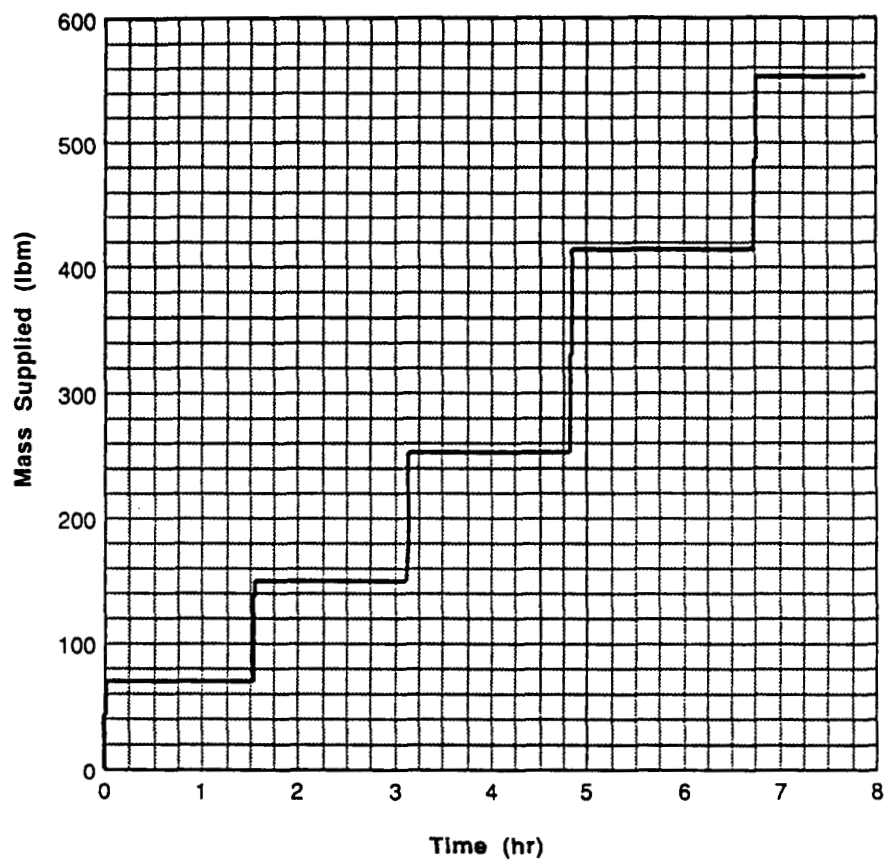


Figure 3-22. Profile of Mass used During Prechill of a 100 Klb. LH2 Tank Set

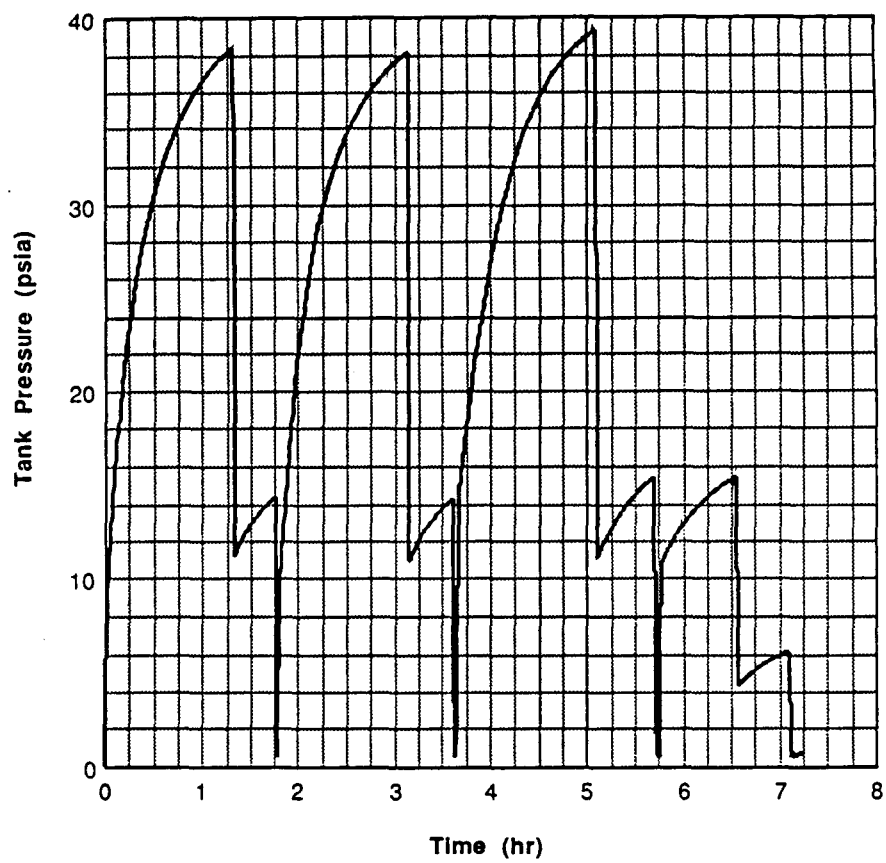


Figure 3-23. Tank Pressure History During Prechill of a 200 Klb. LH2 Tank Set

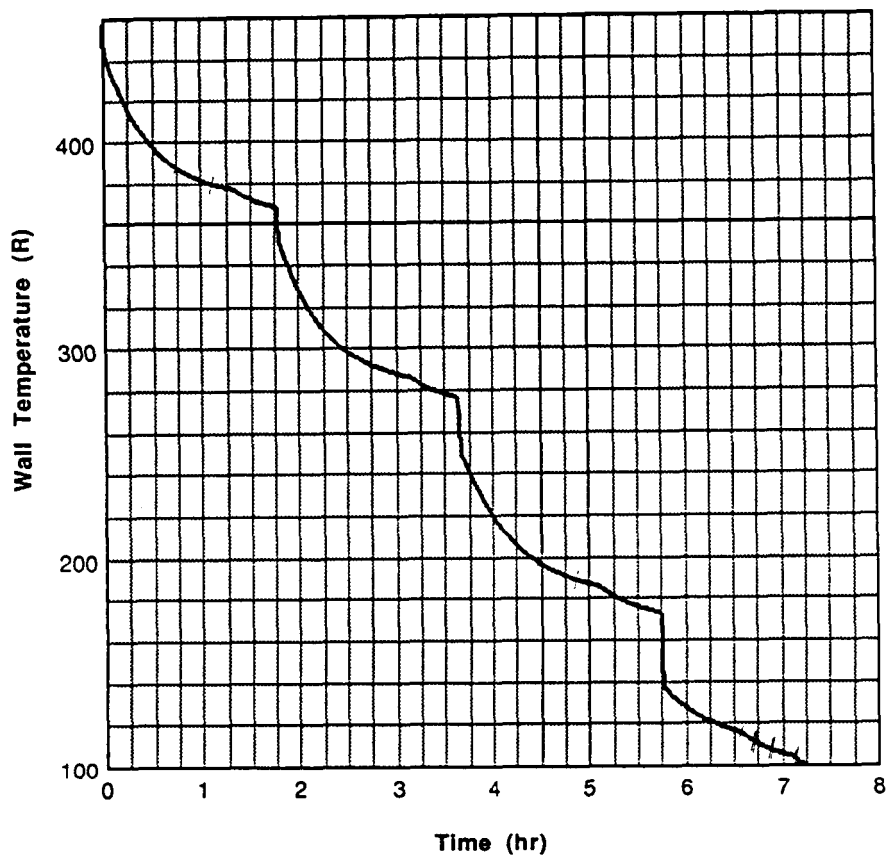


Figure 3-24. Tank Wall Temperature History During Prechill of a 200 Klb. LH2 Tank Set

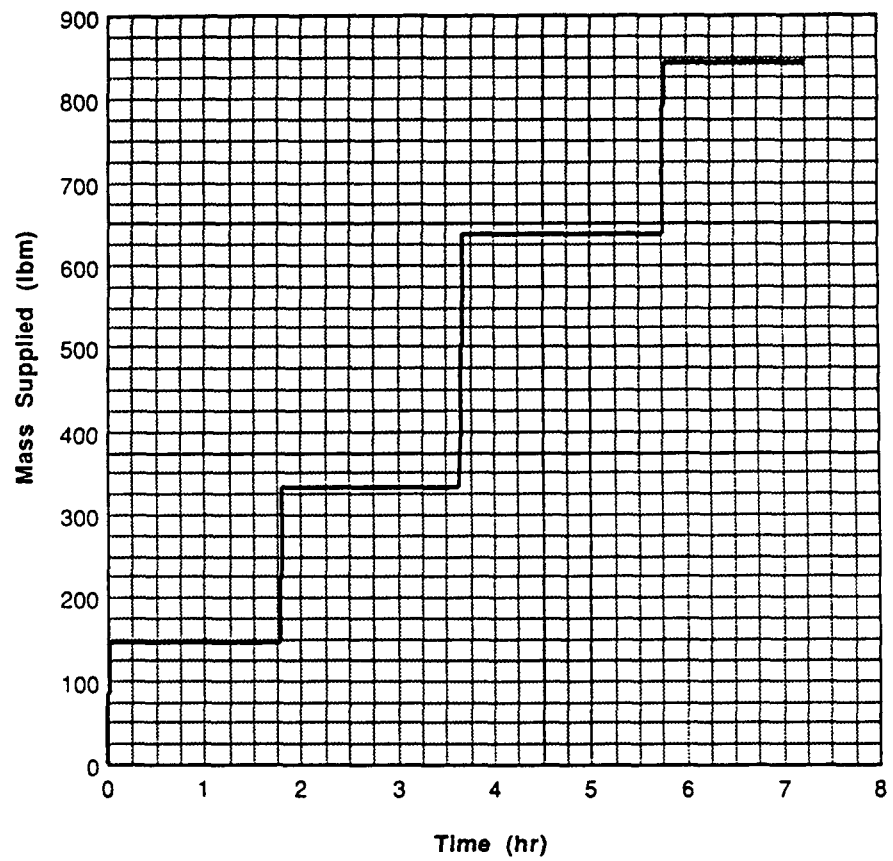


Figure 3-25. Profile of Mass used During Prechill of a 200 Kib. LH2 Tank Set

prechill took nearly 10 hours to reduce the tankwall/ullage temperature from 460R to 230R. The sensible and latent heat capabilities of LO2 are so low compared to LH2 however, that the "hold" portion of the process results in very little reduction in tank wall/ullage temperature, and hence the hold period is a very inefficient use of time. The reduction in wall/ullage temperature occurs only during the brief time period immediately following the charge (injection of saturation liquid oxygen) process. Eliminating most of the hold process resulted in a prechill time of 39 minutes, requiring a total injected mass of 2937 lb of LO2. Allowing the hold process in an attempt to decrease the total injected mass requirement resulted in a prechill time of 9.2 hours, and a total injected mass of 2692 lb. Therefore, it is recommended that a charge, minimal hold, vent procedure be used for LO2 tank prechill, since only a modest 8 % of injected LO2 can be saved, while increasing the prechill time from 39 minutes to 9.2 hours.

Once prechilled, the evacuated tanks are locked-up and filled without any additional venting. A steady liquid flow rate was chosen so as to fill the tank in about four hours. The hydrogen tanks were filled to the 95% volume level, from an initial temperature of 100 R using liquid hydrogen supplied at 36.6 R. The oxygen tanks were filled to 97%, from an initial temperature of 200 R using liquid oxygen supplied at 167 R. Profiles of the tank pressure, wall temperature, and liquid temperature for the 100klb hydrogen tank are shown in Figures 3-26 through 3-28. Corresponding figures for the 200klb hydrogen tank, 100klb oxygen tank, and 200klb oxygen tank are shown in Figures 3-29 through 3-37. The final tank pressure is ~15 psia for the hydrogen cases and is dependent on the initial tank temperature, which was 100 R for the cases shown. The initial pressure rise for the oxygen cases is more rapid than for the hydrogen cases. This difference is due to the lower latent heat of oxygen and the greater specific heat of the aluminum tank wall at liquid oxygen temperatures. The final tank pressure for the oxygen cases is ~20 psia, and is dependent on the initial tank temperature, which was 200 R. The model used in the GDNVF program to predict the final stages of the oxygen fill is currently being tested and improved.

3.4 FLUID MANAGEMENT OPTIONS SUMMARY

3.4.1 NON-CRYOGENIC. In providing the SS attached experiments with required fluids, there are advantages and disadvantages for all approaches, and options range from ORU replacement to hard fluid connections between bulk fluid carriers and each experiment/user attached to the SS.

For experiments which are not attached to (but will receive fluid servicing from) the SS, hard lines are

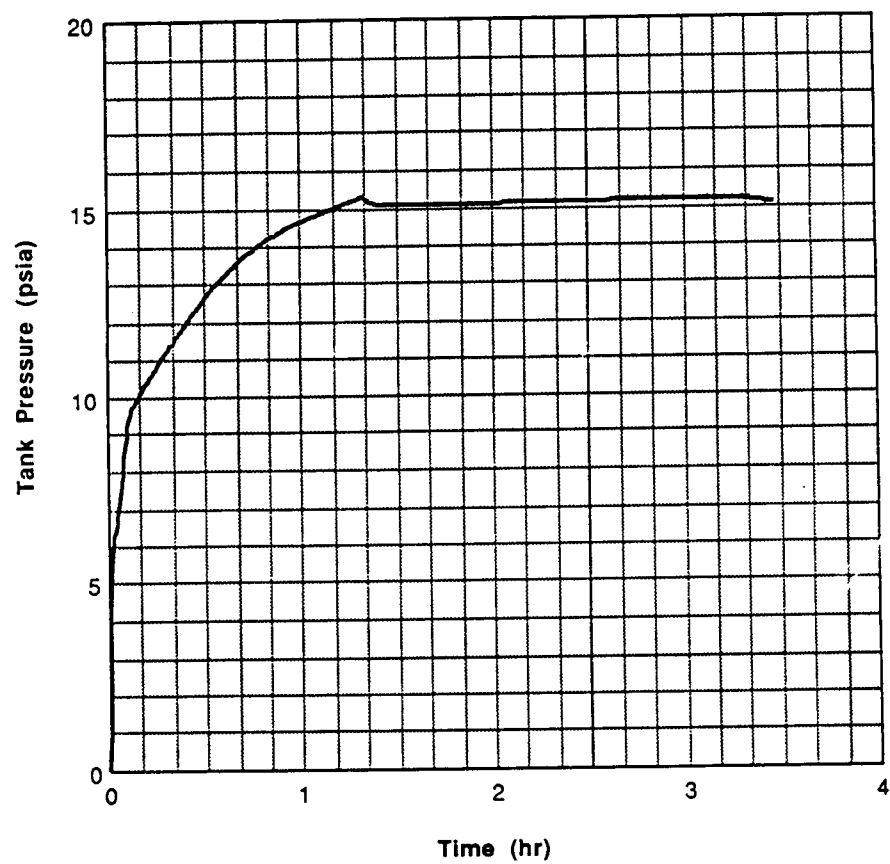


Figure 3-26. Tank Pressure History During Fill of Prechilled 100 Kib. LH2 Tank Set

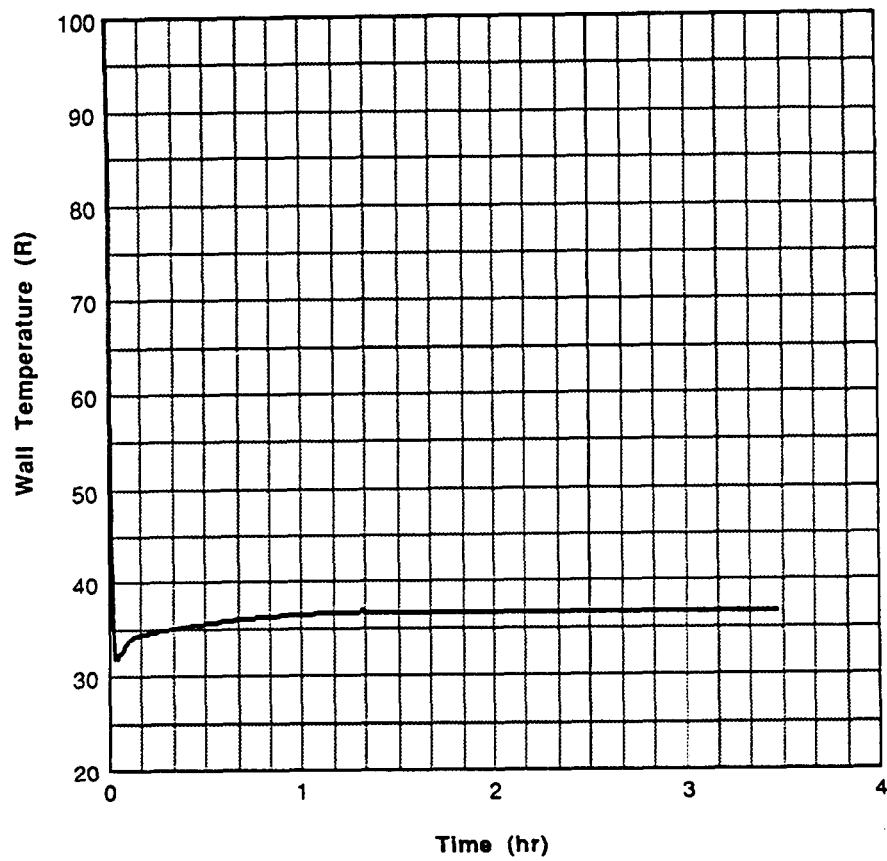


Figure 3-27. Tank Wall Temperature History During Fill of Prechilled 100Klb. LH2 Tank Set

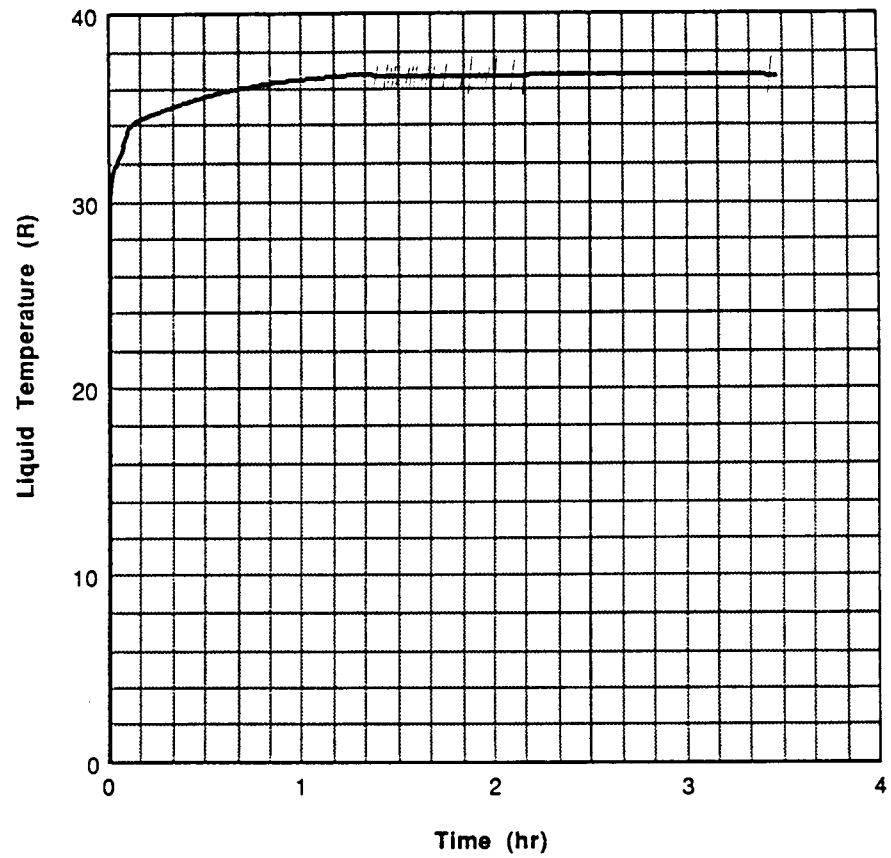


Figure 3-28. Liquid Temperature History During Fill of Prechilled 100Klb. LH2 Tank Set

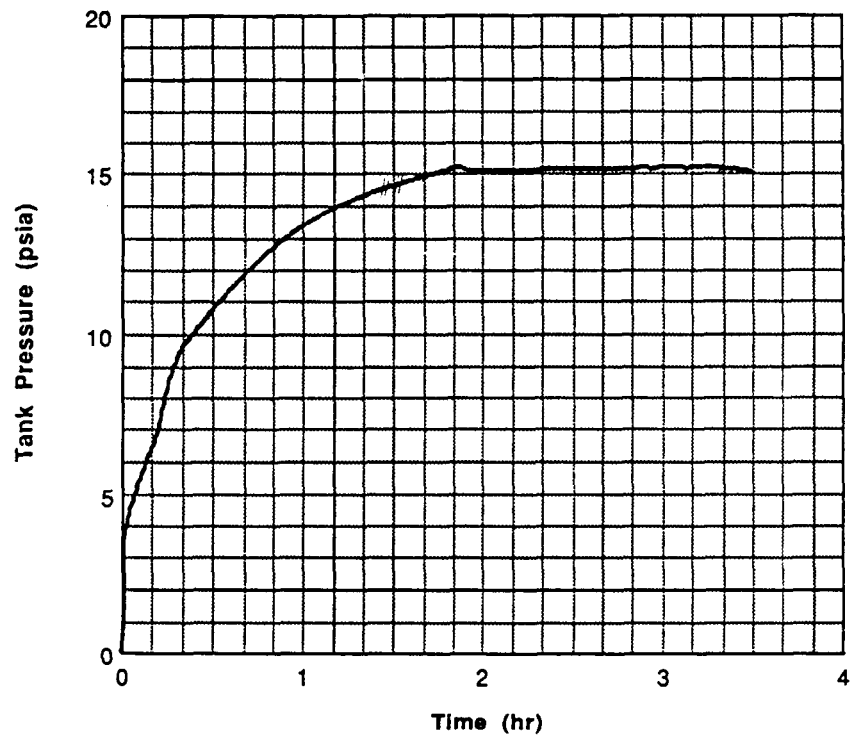


Figure 3-29. Tank Pressure History During Fill of Prechilled 200 Klb. LH2 Tank Set

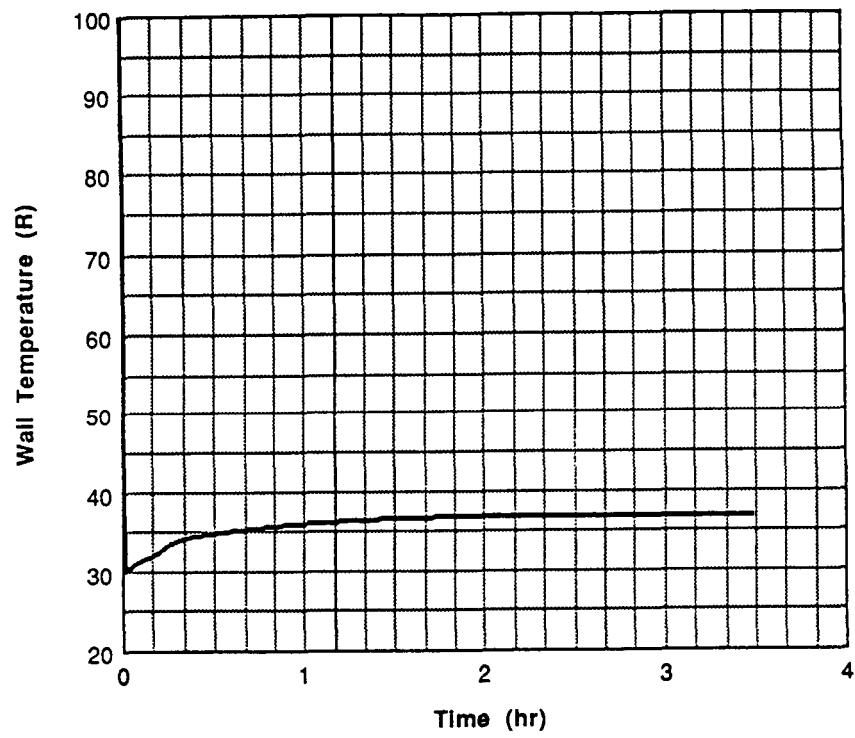


Figure 3-30. Tank Wall Temperature History During Fill of Prechilled 200Klb. LH2 Tank Set

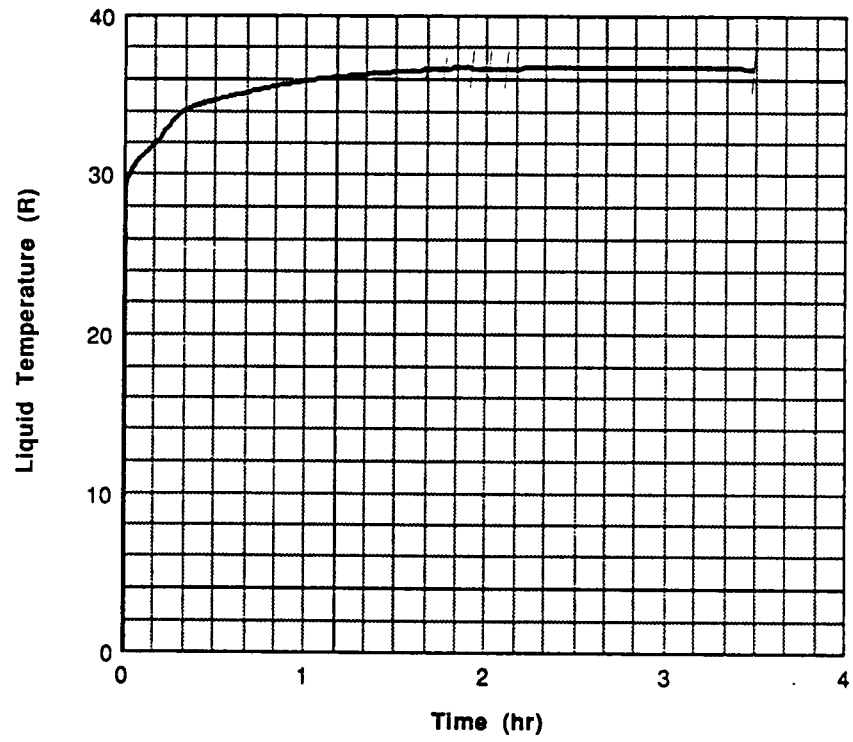


Figure 3-31. Liquid Temperature History During Fill of Prechilled 200Klb. LH2 Tank Set

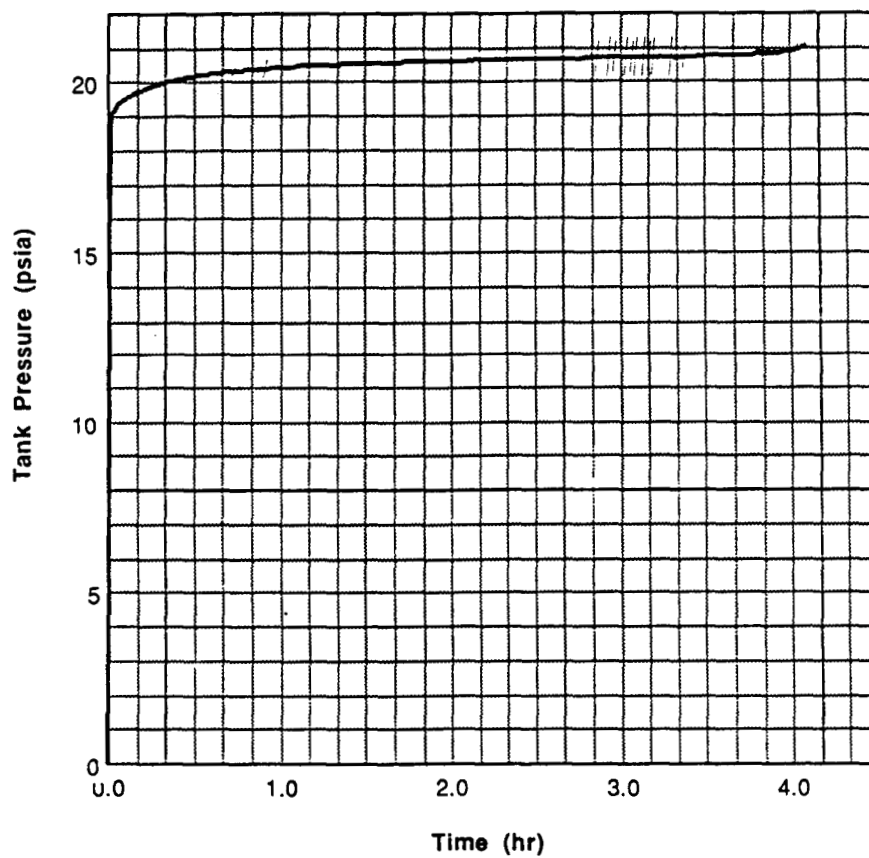


Figure 3-32. Tank Pressure History During Fill of Prechilled 100 Kib. LO2 Tank Set

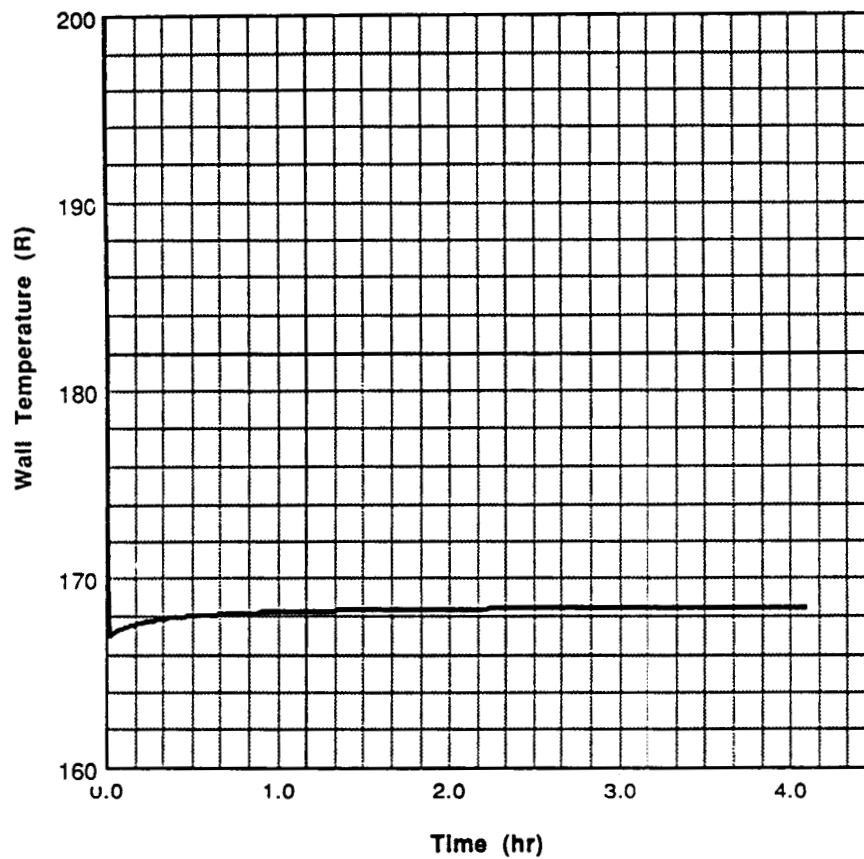


Figure 3-33. Tank Wall Temperature History During Fill of Prechilled 100Klb. LO2 Tank Set

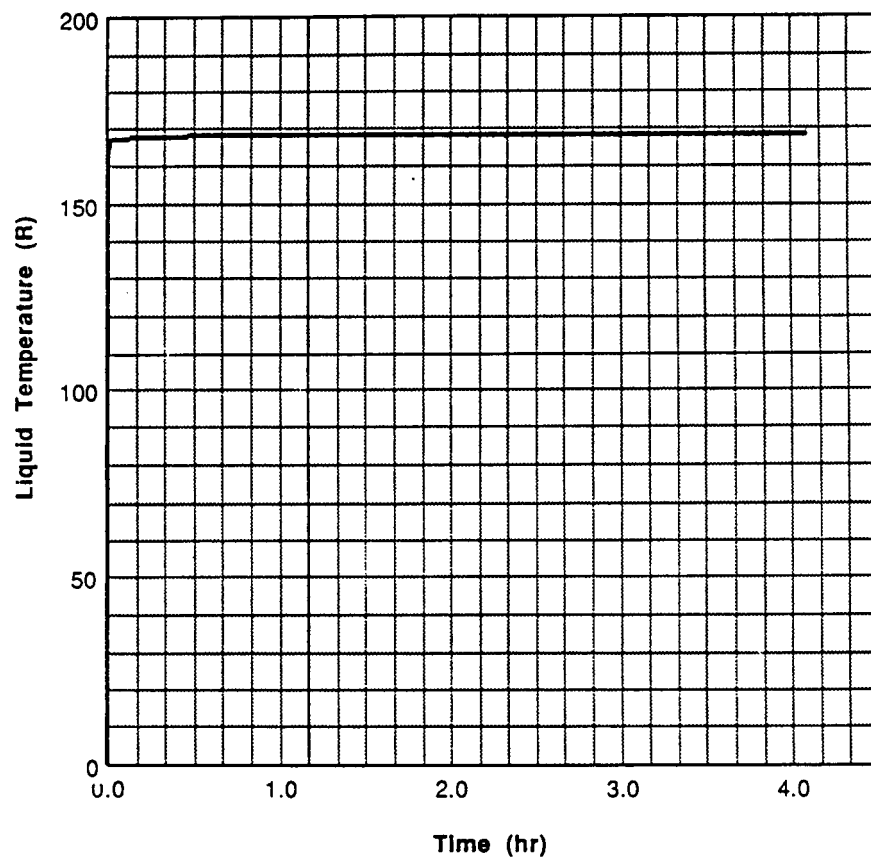


Figure 3-34. Liquid Temperature History During Fill of Prechilled 100Klb. LO2 Tank Set

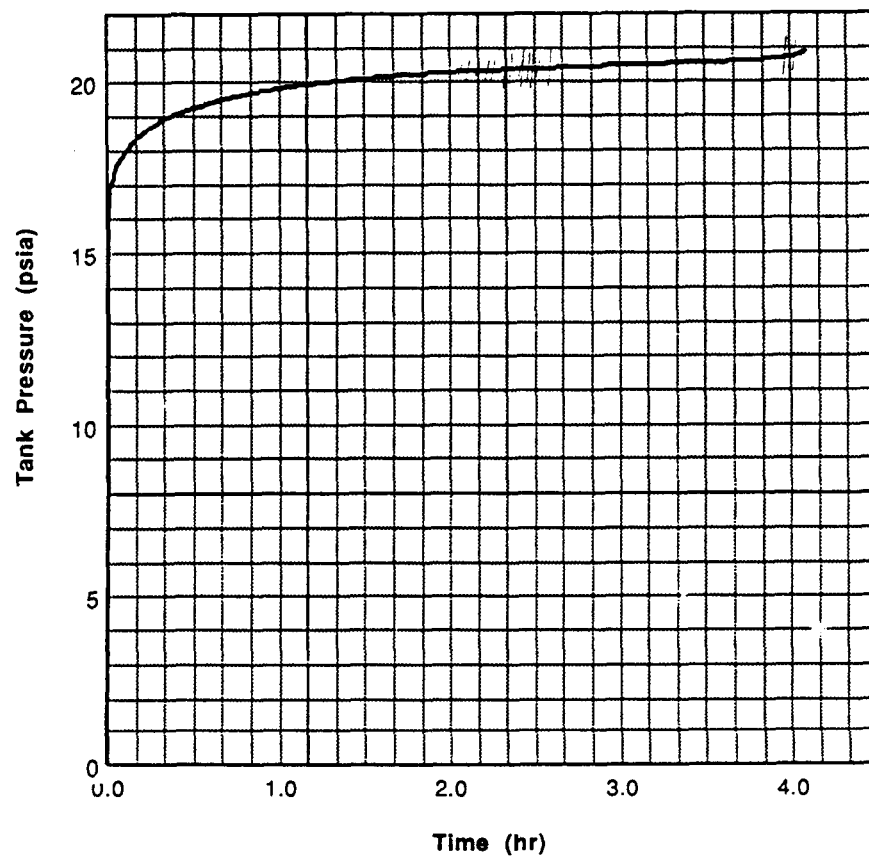


Figure 3-35. Tank Pressure History During Fill of Prechilled 200 Klb. LO2 Tank Set

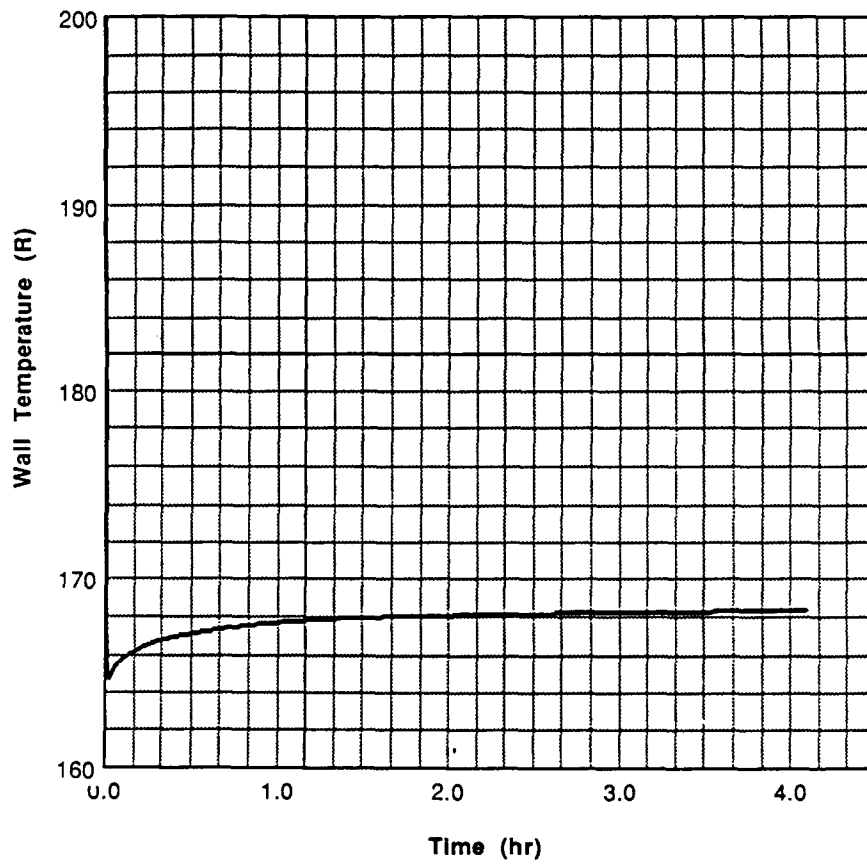


Figure 3-36. Tank Wall Temperature History During Fill of Prechilled 200Klb. LO2 Tank Set

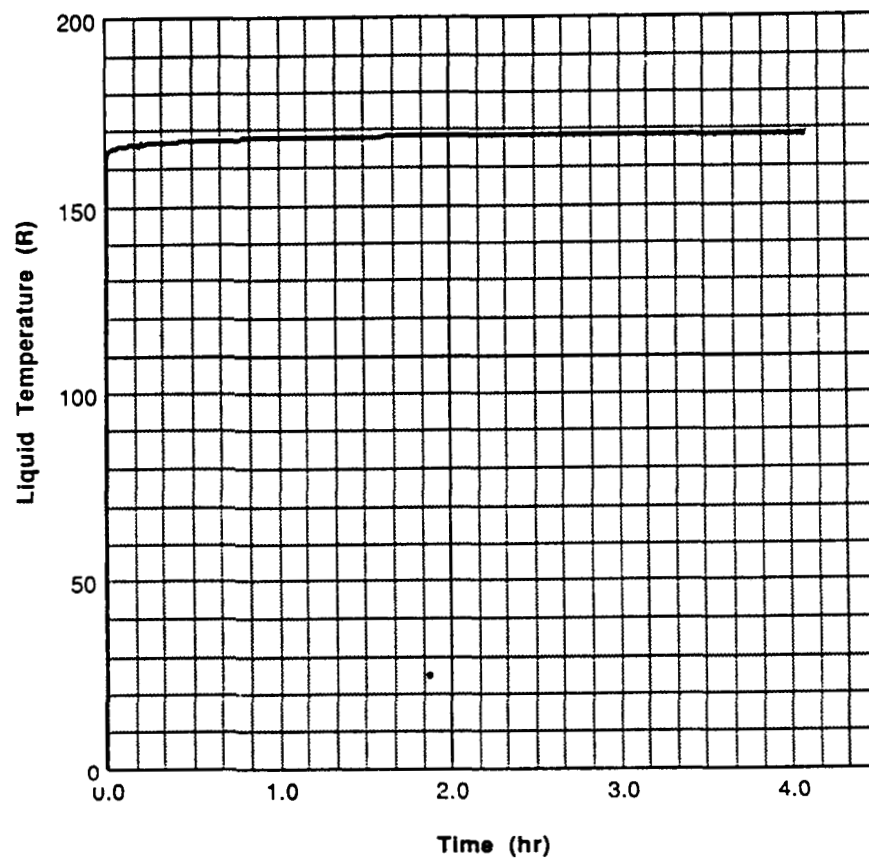


Figure 3-37. Liquid Temperature History During Fill of Prechilled 200Klb. LO2 Tank Set

obviously unacceptable. If fluid provisioning from the SS is assumed, each experiment must be moved to the SS rather than transporting a fluid delivery tanker (which either contains the only fluid required for that particular user, or "drags" along a large amount of other fluids package with the required fluid on the fluid carrier, resulting in inefficiencies) to each user. This also may be advantageous if other servicing must be performed on the experiment at the Customer Servicing Facility (CSF) or other servicing point.

3.4.2 CRYOGENIC. In the case of LHe servicing for attached payloads/experiments, ORUs are not practical due to serious performance deficiencies (large fluid waste penalty) associated with the storage of LHe in typically small ORU vessels. Co-location of LHe users near a centrally located LHe carrier was considered, as well as simply replenishing the individual experiments with a STS or expendable launched tanker.

The ASTROMAG experiment is a major user of LHe. A dedicated storage dewar system concept (to resupply the experiment via STS or expendable-launched tanker) is already planned by NASA-GSFC under the Liquid Helium Storage Facility (LHSF) program. A facility such as this could be incorporated into a LHe carrier concept similar to the one shown in Figure 3-7, and thus be used to provide AXAF, LDR, and SIRTf LHe needs as well. The design features and operations required for LHe management are rather complex (and critical for LHe II), and overall operations and performance could be improved by co-location of LHe facilities/users. The unattached LHe experiments could be docked near the LHe carrier (which should be adjacent to the ASTROMAG and all other attached to SS users of LHe), connected to it by hard (or at least thermally guarded) transfer lines using "quick disconnect" fluid lines and other required support equipment, and refilled.

The provisioning of propellant for cryogenic vehicles will be required for STV, Planetary Initiatives, and Code Z missions. Due to the large LH2 and LO2 (and some Argon, Hydrazine) quantities involved, unmanned co-orbiting refueling platforms have been conceptually designed, which are based on LTCSF storage tankset technology. STV and Code Z propellant storage platforms are presented, which are sized for each particular mission model.

Predictions of LH2 and LO2 tankset performance using the GDSS computer code COOLANT have been presented. The results indicate that a 100klb capacity tankset LH2 tank can be prechilled (8 hours, 460R to 100R) and filled (4 hours) in less than 12 hours total. Because of the fluid properties of LO2, prechilling must be done from 460R to only 250R, but still requires about 8 hours because of the lower sensible and latent heat of LO2. Filling of the O2 tank may also be accomplished within 4

hours. These estimates provided a basis for an operations timeline, presented in Section 4 of this report.

The steady-state boiloff rates for LH2/LO2 for the 100 and 200klb tanksets have been reported for a range of environments, and are all less than 0.4% per month by weight.

Required ullage pressurant quantities for transfer of 7500 lb of LH2 from a storage tankset into a user tank (i.e. STV vehicle) have been estimated. The effects of initial supply tank fluid levels, collapse factor, and pressurant gas inlet temperature have been reported also. The total pressurant required and in general the entire transfer process, is very sensitive to these variables.

4

FLUID PROVISIONING APPROACH SELECTION

The trade studies and comparisons of the alternate experimental and propellant fluid provisioning approaches reported in Section 3 support the rationale and "baseline" approach presented in this section. Defining an optimal experimental fluid management strategy is difficult because many issues concerning the experimental payload replenishment have yet to be resolved. However, a recommended strategy for supporting IOC through growth SS attached experimental fluid requirements has been defined. While these recommendations are preliminary in nature, they do provide a consistent approach to providing all fluid requirements to NASA's currently planned Space Station objectives between 1994 and 2018 (and beyond) via an "evolvable architecture".

4.1 EXPERIMENTAL FLUID PROVISIONING APPROACH SELECTION

The transport and storage of over 250,000 liters (62,000 kg) of fluids is required to meet US and international experimental payload fluid requirements from 1994 through the year 2011. These fluids must be brought from earth, and for this study have been assumed to be delivered by fluid carriers similar to those presented in Section 3. Requirements analyses indicate a total launch requirement of a total of 30 fluid carriers through the year 2011, at a rate of 1 to 4 carriers per year. For this study, is assumed that the Station will support the resupply and maintenance of free flying experiments.

Since initially most of the experimental fluid requirements are quite low, it is recommended that fluids should be provided for by the removal and replacement of ORUs by EVA, in a manner similar to that used to replace film, batteries, etc. with ORUs for the various experiments. As fluid needs increase, there may be an economic incentive to adopt an integrated fluid subsystem approach, which would use hard lines on the SS truss to connect experiments to a central fluid storage tank. Such a system is planned for the IOC SS for nitrogen, called the INS (Integrated Nitrogen System). The economic "break points" for the incorporation of such a system is determined by use rates, commonality, and life cycle costs (capital and operating standpoints).

If a Customer Servicing Facility (CSF) is going to be used to service free flyers, the attached payloads could be serviced there also. Certain fluid carriers could then be placed near the CSF which would minimize transfer line lengths or MRMS travel distance/operations requirements. Standardized fluid interfaces and automatic coupling devices could be used for fluid transfer within the CSF. It is likely

that a experimental payload fluid resupply strategy will evolve to the point where a combination of approaches are used.

Assembly layouts of the IOC and growth Space Stations are shown in Figures 4-1 and 4-2. The drawings include locations for the attached experiments on both the IOC and growth stations, and the necessary fluid carriers, interfaces, and structural implications of the IOC to growth evolution (i.e. experiment relocation, viewing considerations, additional truss elements, etc.).

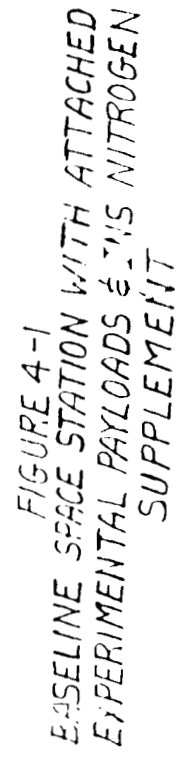
4.1.1 NITROGEN. The IOC Space Station will have an Integrated Nitrogen System (INS) that will supply nitrogen to the lab modules, the ECLSS, and to other locations at the SS (i.e. airlocks, etc.). Figure 3-3 shows a schematic of the proposed INS.

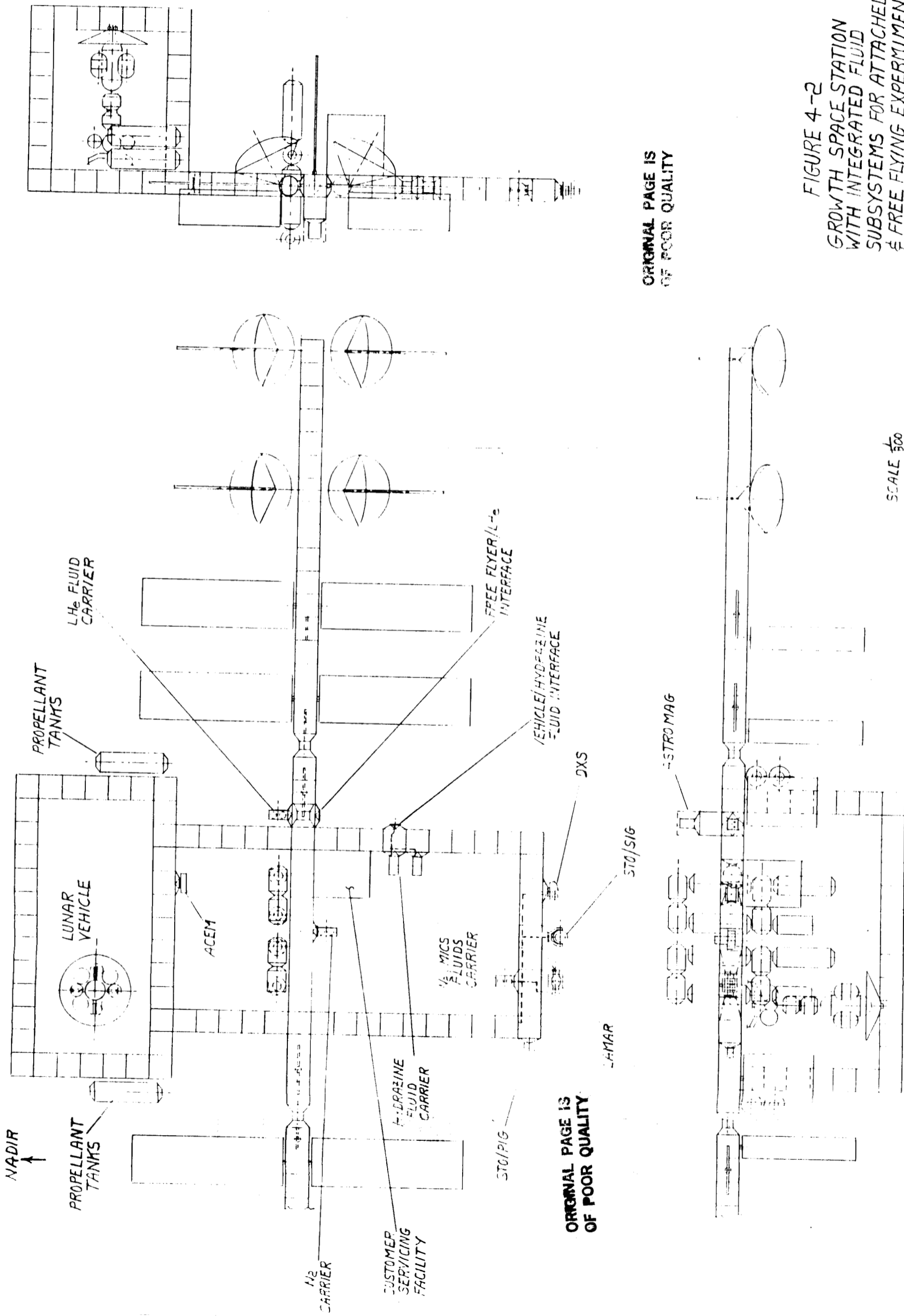
The INS will have a fluid interface to allow connection with the "on-orbit storage tank" (which does not have a specified capacity/design configuration at this time), which is essentially a surge volume/storage container for the resident N₂. A similar interface could be used to allow transfer of N₂ from a N₂ fluid carrier to increase the capacity of the INS. This approach allows growth of the INS to support growth users which are not present on the IOC SS. Attached experiments could be supplied via hard lines of the INS, and free-flyers could be refilled telerobotically at a fluid interface panel/docking adaptor. The INS system is described in Reference 4-1.

ORU replacement would support the IOC SS experiment requirements, and as users/rates increase, this approach could evolve into the direct connection of experiments requiring nitrogen with the INS (Integrated Nitrogen System). Depending on the rate at which the user requirements grow, N₂ carriers could be delivered to the SS to interface with the INS, to supplement its' N₂ storage capacity to meet the new requirements.

The recommended approach will consist of a N₂ carrier mounted near the common and habitation modules on the main boom, and will interface with the INS. Nitrogen use rates will grow rapidly as OMV and /or ACEM cold N₂ gas thruster rates increase for movement of propellant storage tank sets in the vicinity of the SS.

4.1.2 METHANE, ARGON, XENON, AND "RARE GAS". ORU replacement would support the IOC SS experiment requirements for these fluids, and as users/rates increase, this approach could evolve into; 1) the use of a dedicated carrier containing bulk supplies of gases used to recharge the ORU gas containers (rather than returning the empty ORUs to earth), and eventually 2) the construction of



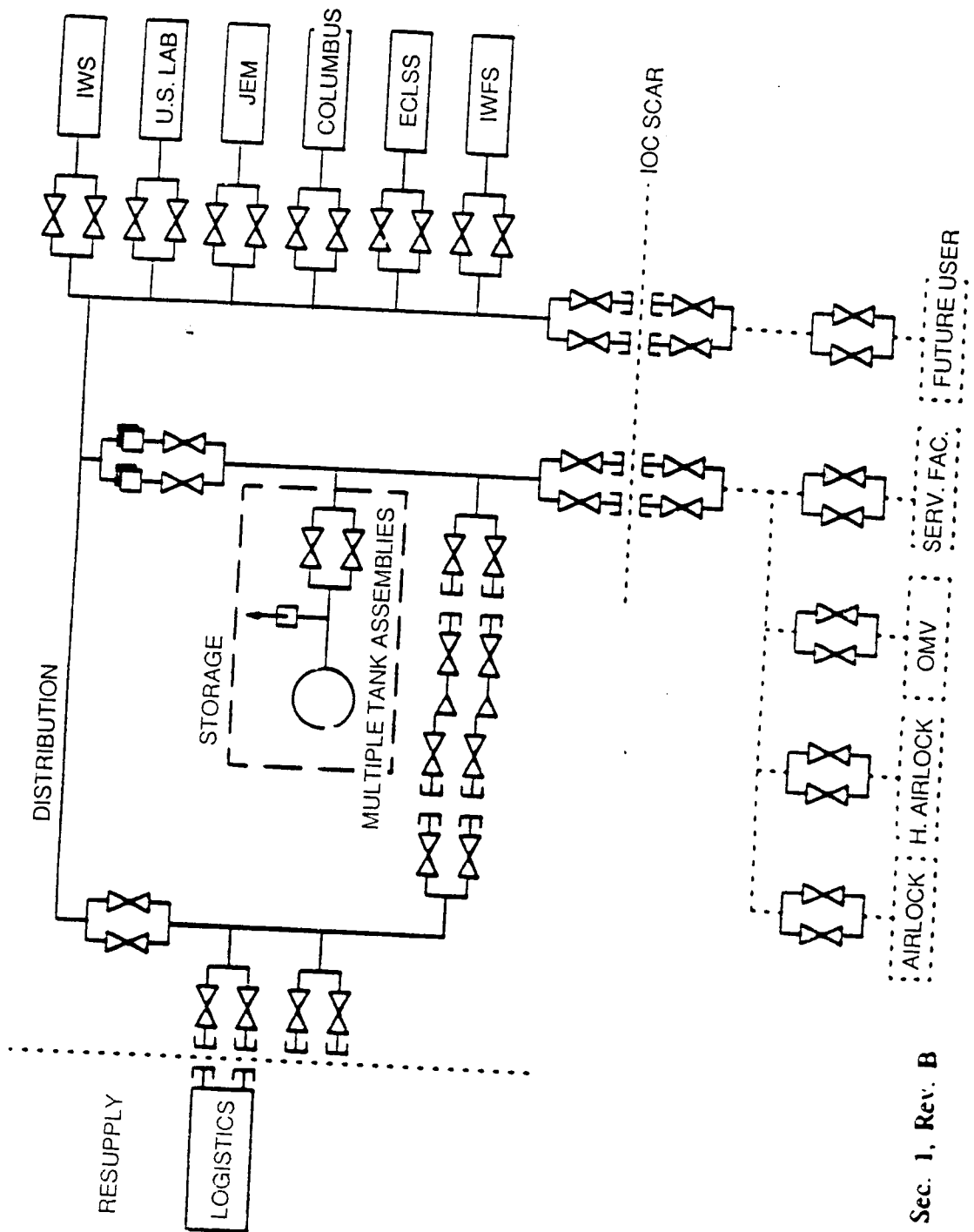


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FIGURE 4-2
GROWTH SPACE STATION
WITH INTEGRATED FLUID
SUBSYSTEMS FOR ATTACHED
& FREE FLYING EXPERIMENT
FLUID RESUPPLY

SCALE 500



SSP 30264, Sec. 1, Rev. B

Figure 4-3. Baseline Space Station Integrated Nitrogen System (INS) Hardware Schematic

4.2.1 PROPELLANT TANKS ATTACHED TO SPACE STATION. Since the charter of this study is to identify the impacts of fluid delivery, storage, and transfer at the SS, STV mission model propellant provisioning from the SS was considered. It has also been suggested that a Lunar mission could be supported by SS propellant, but the STV mission model was used for the operations analysis that follows.

It is noteworthy that two, fully loaded 200klb capacity tanksets (which provides sufficient capacity for the STV mission model, as defined by a "modified Revision 8 "STV mission model) weigh nearly 520klb including structure. This weight is on the same order as the IOC SS Freedom, which is estimated to be approximately 500klb. Storage of Mars, Lunar and other Code Z propellant at the SS is considered by NASA to be impractical, the modified STV mission model was selected to provide fluid requirements for SS propellant storage.

The scenario investigated a Station based STV which has all the maintenance, integration and refueling capabilities. Delivery of the propellant to the Station was analyzed, using the LTCSF tanksets due to the design data available on them. The tanks would be carried up on the Shuttle Z vehicle which initially had a payload to Station altitude capability of 193,700 lbs. but was resized to a capacity of 308,000 lbs. The payload fairing is 40 feet in diameter by 50 feet long. Using only currently defined LTCSF tank configurations, resupply analyses were performed with the 140klb capacity version initially and later with the 200klb capacity. These tanksets have a total wet (fully fueled) weight of 177klb and 245.5k lbs, respectively. These scenarios require that the OMV rendezvous with the tankset and ferry it to the Station. However, the OMV has been designed for a maximum payload weight of 75k lbs., assuming no maneuvering requirements. Bringing the tank to the Station requires positive attitude control throughout the transfer and the use of cold gas during the final approach for contamination reduction.

In order to increase the OMVs capability with minimum development costs, we have developed an Attitude Control Enhancement Module (ACEM) design concept as shown in Figure 4-4. The ACEM is attached to the front of (and controlled by) the OMV. To minimize the impact to the OMV, the ACEM will have its own batteries, signal processor and thruster control hardware and software, but it will rely on the OMV for guidance, navigation and control information. The OMV will relay the commands sent from the ground or Station to the ACEM.

The ACEM will have two deployable S-Band omnidirectional antennas capable of extending beyond

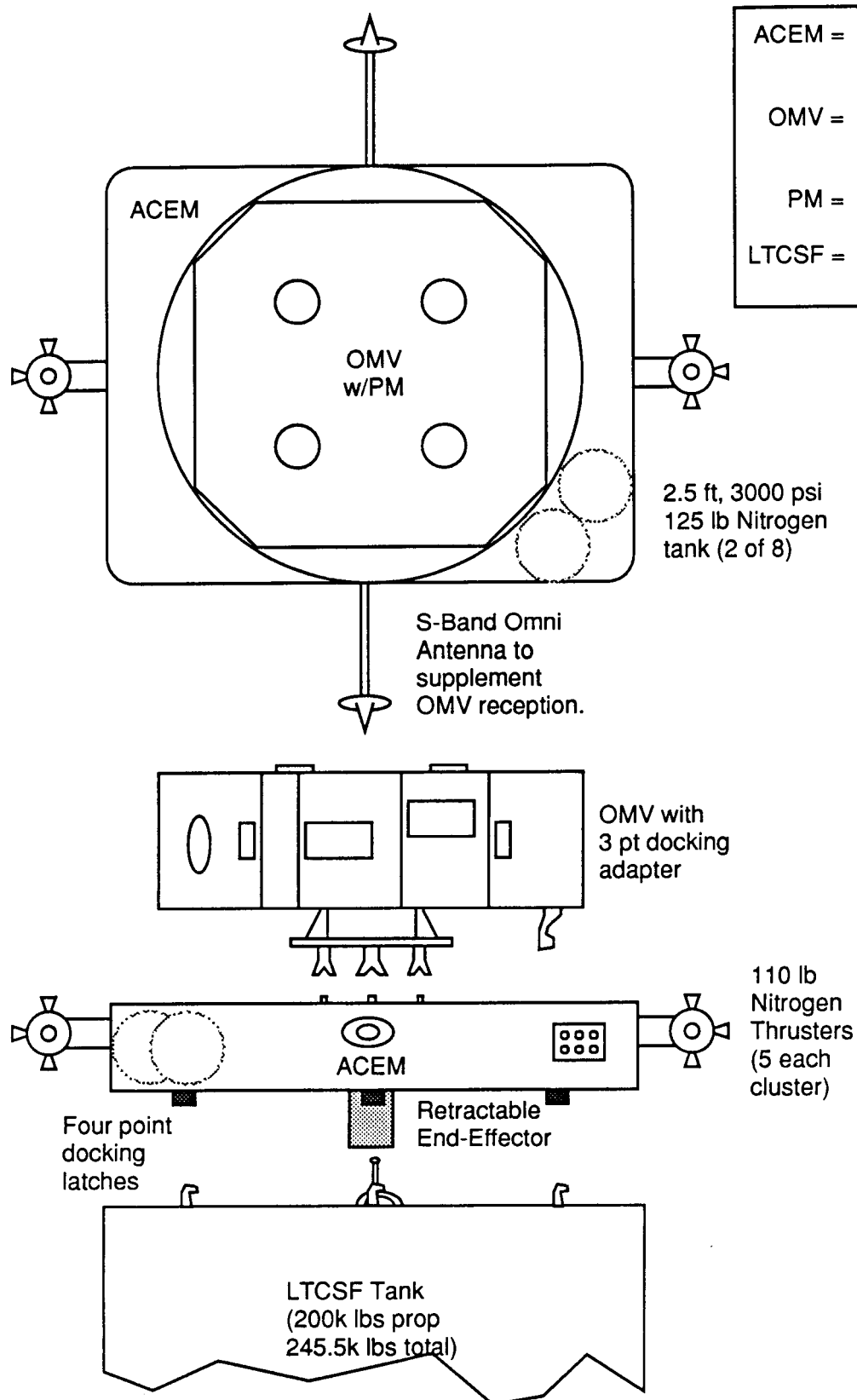


Figure 4-4. Attitude Control Enhancement Module Layout.

the diameter of the tanks to allow the OMV to communicate continuously with TDRSS and (or) the Space Station. Two thruster pods, each containing five 110 lb. thrust nitrogen thrusters, will also extend beyond the tank diameter. This will provide three axis control for the tank with sufficient force to allow yawing the tank 180° in about three minutes. The ACEM will carry a total of 1000 lbs. of nitrogen in eight 2.5 ft. tanks. These tanks will be refilled at the Station.

The scenario for delivery of the tankset to the Station is depicted in Figures 4-5 and 4-6. Figure 4-5 shows the delivery of the tank to the Station rendezvous zone by the Shuttle-Z third stage. The OMV/ACEM assembly travels from the Station, rendezvous and docks with the LTCSF tankset, and stabilizes it. The OMV performs a burn with its main thrusters for about 20 minutes to initiate the phasing to bring the tank to the Station. Prior to arriving at the proximity zone, the tank is oriented and a burn is performed to co-orbit the tank with the Station. The ACEM cold gas thrusters perform the maneuvers to bring the tank within reach of the MRMS. Figure 4-6 shows the delivery operations inside the proximity operations zone.

Figure 4-7 shows the refueling scenario for the STV at the SS. A detailed operational timeline of the tank delivery process along with the STV operations at the Station is shown in Table 4-1. The Table includes times for both reboost and microgravity propellant acquisition systems. Microgravity methods require capillary devices for propellant acquisition, and the reboost alternative provides propellant settling induced by acceleration of the SS. The delivery operations and times will be the same for the 140klb and 200klb tanksets.

Two methods of propellant transfer from the Station to the STV were investigated. One is microgravity transfer and the other is settled transfer during reboost. If strictly microgravity, a capillary liquid acquisition device is preferred and it requires the tanks and STV to contain liquid acquisition devices (LADs) and other special design features. It is uncertain, however, how the LAD will behave under the accelerations the Station will experience during reboost. It is possible for the LAD to dry out in localized regions, thereby decreasing or hindering its performance.

The propellant settling that occurs during reboost may be used to allow settled STV tanking operations to occur during SS reboost periods. The settling of the propellant would allow pumping of the fluids between the storage tanks and the vehicle, since the location of the ullage and liquid within the tanks would be known. This, however would restrict tanking operations to periods of reboost, which may result in unacceptable operational constraints.

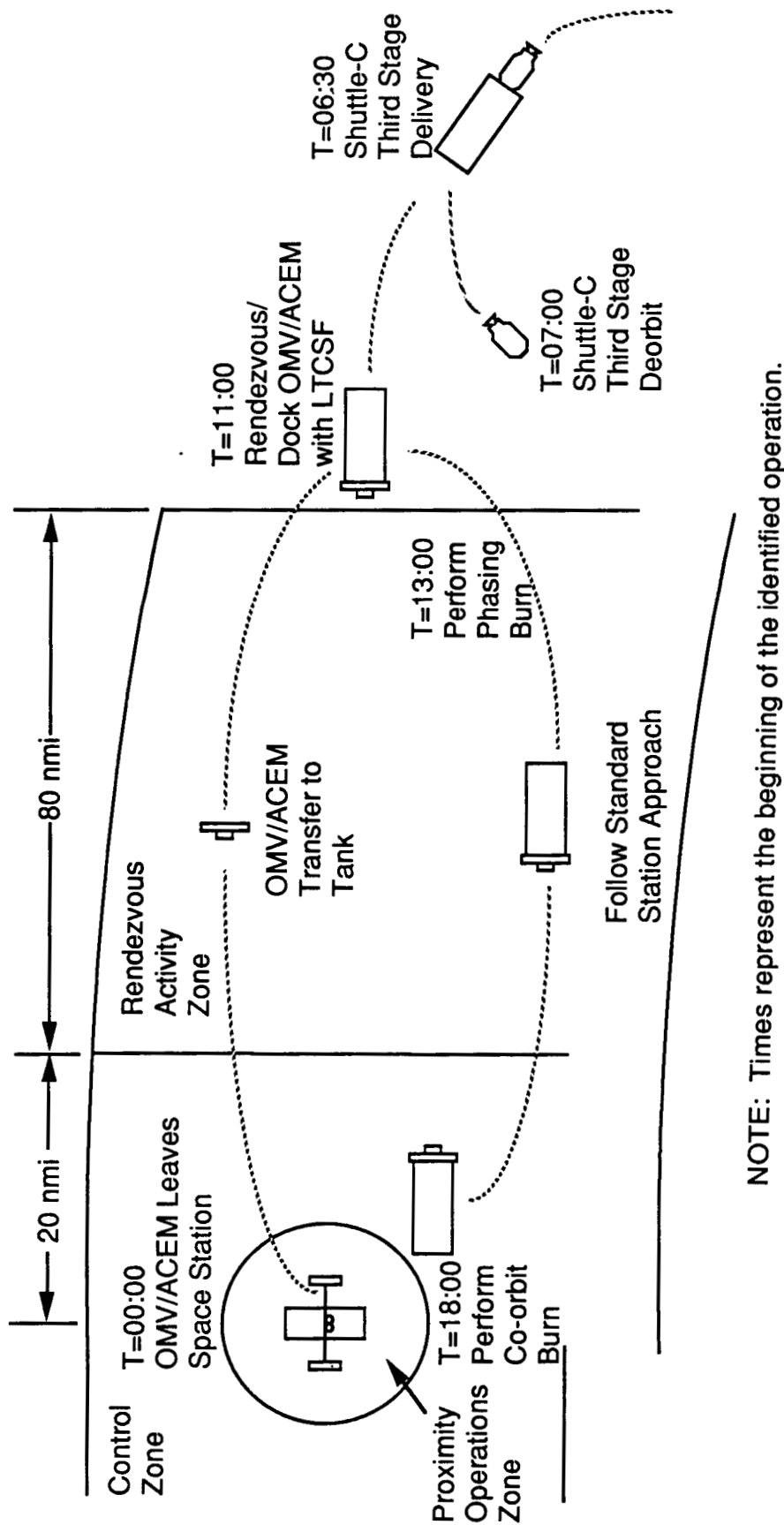
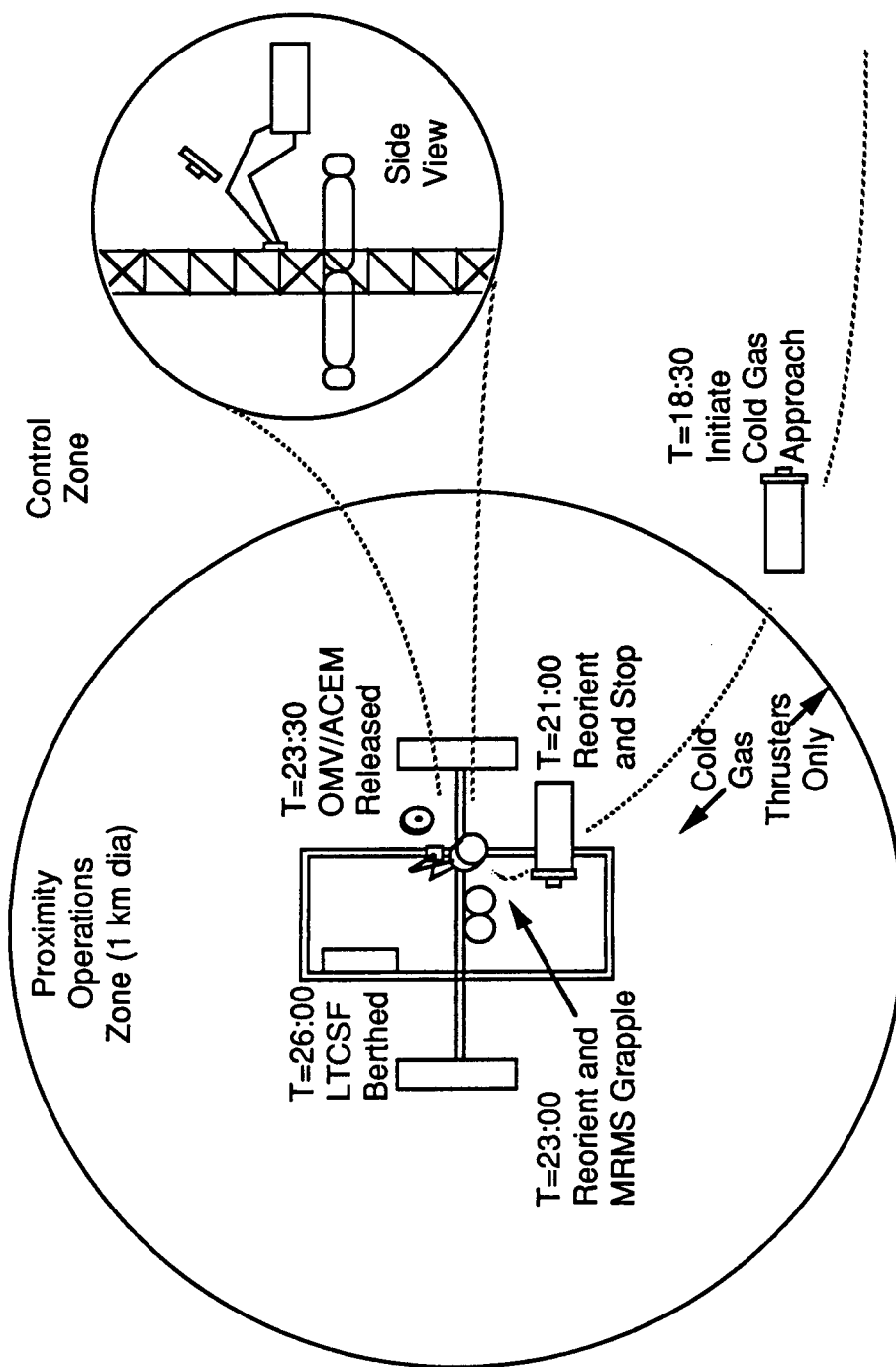


Figure 4-5. Delivery Operations for LTCSF to Space Station.



NOTE: Times represent the beginning of the identified operation.

Figure 4-6. Rendezvous and Docking Operations for LTCSF Delivery.

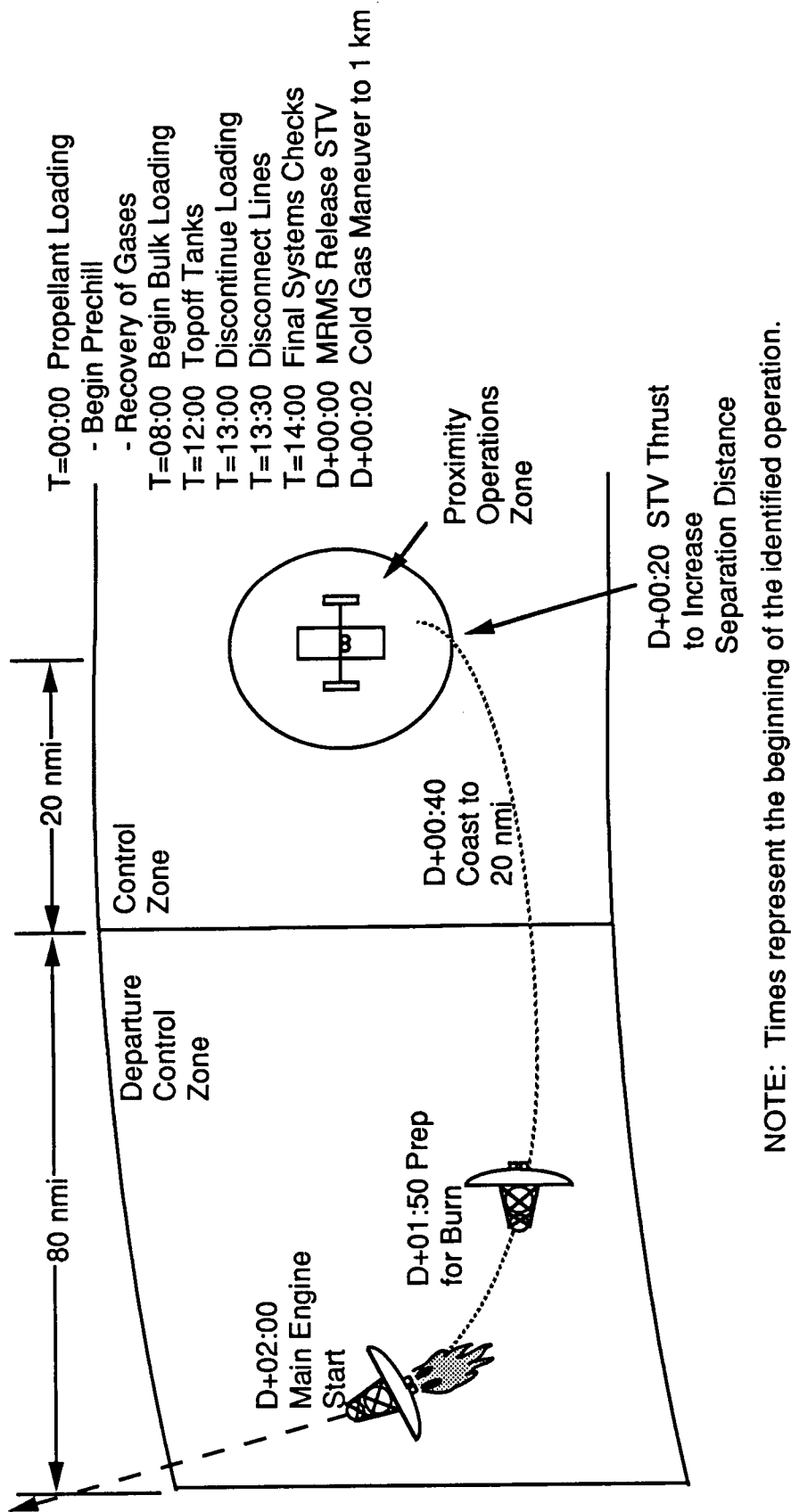


Figure 4-7. STV Deployment Operations from the Space Station.

Table 4-1. LTCSF Propellant Tankset Delivery and Berthing to SS; Launch of STV from SS - Timeline

Item	Event Description	Start	Duration	EVA	IVA	OMV	RMS	Ground
1	Preparation of Station for Tank Delivery	TD -60:30						
2	Verify command and comm lines to tank area	-60:30	1:00		1:00			
3	Inspect hard attach points (IVA)	-59:30	4:00		4:00			
4	Prepare empty tank for disconnect	-55:30	1:00		1:00			
5	OMV attaches to empty tank	-54:30	4:00		4:00	4:00		
6	MRMS attaches to tank and disconnects from SS	-50:30	2:00			2:00	2:00	
7	OMV maneuvers tank away from Station	-48:30	1:00		1:00	1:00		
8	OMV deorbits empty tank	-47:30	1:30			12:00		12:00
9	OMV returns to Station, refuels	-46:00	12:00		6:00	12:00		8:00
10	ACEM nitrogen tanks filled	-34:00	2:00		2:00			
11	Repairs/Maintenance to depot area performed	-32:00	8:00	6:00	6:00			
12	Communicate Station ready for new tank	-24:00						
RESOURCE TOTALS								
				6:00	25:00	31:00	2:00	20:00
13	Tank Delivery (TD)	TD + 0:00						
14	Launch of Shuttle Z	0:00						
15	Perform ascent	0:00	0:15					
16	Perform maneuver to Station altitude co-orbit	0:15	0:45					
17	Perform phasing to edge of Rendezvous Zone	1:00	4:30					4:30
18	Ground/Station control/monitor operations	5:30	1:00		1:00			1:00
19	Separate tank from Shuttle Z third stage	6:30	0:00					
20	Tank maintains pressure control	6:30						
21	Shuttle Z third stage maneuvers away	6:30	0:30					0:30
22	Shuttle Z third stage deorbits	7:00	1:00					
RESOURCE TOTALS								
				0:00	1:00	0:00	0:00	6:00
23	OMV Begins Ferry Operations	TD + 1:00						
24	MRMS mates OMV with ACEM	1:00	4:00		4:00	4:00	4:00	
25	OMV/ACEM performs interface checks	5:00	2:00		2:00	2:00		2:00
26	OMV/ACEM departs Station	7:00	1:00		1:00	1:00		1:00
27	Ground controls to rendezvous with cargo	8:00	3:00			3:00		3:00
28	OMV/ACEM docks with tank	11:00	0:30			0:30		0:30
29	ACEM deploys auxiliary antennas	11:30	0:00			0:00		
30	Ground controls ACEM thrusters through OMV	11:30						
31	Tank stabilized and in attitude hold	12:00	1:00			1:00		1:00
32	Ground maneuvers tank to Control Zone	13:00	5:30					

Table 4-1. LTCSF Propellant Tankset Delivery and Berthing to SS; Launch of STV from SS - Timeline (continued)

Item	Event Description	Start	Duration	EVA	IVA	OMV	RMS	Ground
33	OMV performs phasing burn (bi-prop sys)	13:00	0:20			0:20		0:20
34	Cargo Coast, ACEM holds attitude	13:20	4:40			4:40		4:40
35	ACEM orients cargo to co-orbit burn attitude	18:00	0:10			0:10		0:10
36	OMV performs co-orbit burn (bi-prop sys)	18:10	0:20			0:20		0:20
37	Station begins visual cargo maneuvering	18:30	0:45		0:45	0:45		0:45
38	ACEM cold gas system used	18:30						
39	Cargo maneuvered within MRMS range	19:15	0:15		0:15	0:15		0:15
40	Tank oriented for MRMS grapple	19:30	0:10		0:10	0:10	0:10	0:10
41	Tank stabilized and rates diminished	19:40	0:10		0:10	0:10		0:10
RESOURCE TOTALS								
		0:00	8:20	18:20	4:10	14:20		
42	MRMS Grapples Tank and Attaches to Truss	TD + 23:00						
43	MRMS arm 1 attaches to tank edge grapple	23:00	0:30		0:30	0:30	0:30	0:30
44	OMV relinquish control to MRMS	23:30	0:00					
45	MRMS arm 2 attaches to OMV/ACEM	23:30	0:30		0:30	0:30	0:30	0:30
46	OMV/ACEM removed from tank	24:00	1:00		1:00	1:00	1:00	1:00
47	OMV/ACEM station keep near Station	24:00	15:00			15:00		
48	MRMS arm 2 attach to tank centerline grapple	25:00	1:00		1:00	1:00	1:00	1:00
49	Maneuver tank and attach to truss (arms 1 & 2)	26:00	12:00		12:00	12:00	12:00	12:00
50	Confirm all docking attachments	38:00	0:30		0:30	0:30	0:30	0:30
51	Confirm cmd/comm/monitoring	38:00	0:30		0:30	0:30	0:30	0:30
52	OMV/ACEM maneuver to MRMS	39:00	0:30		0:30	0:30	0:30	0:30
53	MRMS grapple OMV/ACEM	39:30	0:30		0:30	0:30	0:30	0:30
54	MRMS berth ACEM	40:00	3:00		3:00	3:00	3:00	3:00
55	MRMS dock and berth OMV	43:00	3:00		3:00	3:00	3:00	3:00
56	Tank/Station Systems Checkout	46:00	1:00		1:00	1:00	1:00	1:00
57	Interface integrity checks	46:00	1:00		1:00	1:00	1:00	1:00
58	Monitor systems and fluids	46:00	1:00		1:00	1:00	1:00	1:00
59	Caution & Warning status to crew							
60	Ground primary monitoring responsibility							
61	Periodic IVA telerobotic inspection							
RESOURCE TOTALS								
		0:00	26:00	24:00	23:00	26:00		
ZERO-G PROPELLANT TRANSFER								
62	STV Operations at Station (STV)	STV + 0:00						
63	STV rendezvous and prox ops	0:00	12:00		2:00			12:00
64	Self ferry to hangar	12:00	2:00		2:00			2:00

Table 4-1. LTCSF Propellant Tankset Delivery and Berthing to SS; Launch of STV from SS - Timeline (continued)

Item	Event Description	Start	Duration	EVA	IVA	OMV	RMS	Ground
65	Docking and Berthing	14:00	6:00	4:00	6:00			6:00
66	Connect interface lines to vehicle	17:00	1:00		1:00			1:00
67	STV checkout and maintenance	20:00	48:00		4:00		2:00	48:00
68	Load payload, check interfaces	68:00	24:00		24:00		20:00	24:00
69	Warn Experiments of Potential Contamination	92:00	0:00					
70	Propellant Loading	95:00	13:00					
71	Ground/Station monitoring	95:00						
72	Begin prechill	95:00	8:00		2:00			8:00
73	Recovery/reliquefaction of gases	95:00						
74	Begin bulk loading	103:00	4:00		2:00			4:00
75	Top off tanks	107:00	1:00		1:00			1:00
76	Discontinue tanking	107:00	0:00					
77	Monitor Status	108:00						
RESOURCE TOTALS								
			4:00	44:00	0:00	22:00		106:00
OR								
REBOOST PROPELLANT TRANSFER								
78	STV Operations at Station (STV)	STV + 0:00						
79	STV rendezvous and prox ops	0:00	12:00		2:00			12:00
80	Self ferry to hangar	12:00	2:00		2:00			2:00
81	Docking and Berthing	14:00	6:00	4:00	6:00			6:00
82	Connect prop lines to STV	17:00	1:00		1:00			1:00
83	STV checkout and maintenance	20:00	48:00		4:00		2:00	48:00
84	Load payload, check interfaces	68:00	24:00		24:00		20:00	24:00
85	Prepare Station for reboost	92:00	0:00					
86	Confirm vehicle ready for prop loading	93:00	1:00		1:00			1:00
87	Begin prechill	94:00	8:00		8:00			8:00
88	Recovery/reliquefaction of gases	94:00						
89	Node Reboost (10E-4 g's)	102:00	10:00					
90	Propellant Settling	102:00	1:00		1:00			1:00
91	Propellant Loading	103:00	3:00					
92	Begin bulk loading	103:00	2:00		2:00			2:00
93	Top off tanks	105:00	1:00		1:00			1:00
94	Discontinue tanking	106:00	0:00					
95	Monitor Status	106:00	6:00		6:00			6:00
96	Node Reboost complete	112:00						
RESOURCE TOTALS								
			4:00	58:00	:00	22:00		112:00

Table 4-1. LTCSF Propellant Tankset Delivery and Berthing to SS; Launch of STV from SS - Timeline (continued)

Item	Event Description	Start	Duration	EVA	IVA	OMV	RMS	Ground
97	STV Deployment Operations (Depl)	Depl-24:00						
98	Ground support deployment	-24:00	22:00					22:00
99	Final flight constants loaded	-2:00	0:30		0:30			0:30
100	Ground/Station GO for separation	-0:30	0:00					
101	STV separates from Station	0:00	0:00					
102	Cold gas maneuver to .6 nmi	0:02	0:18		0:18			0:18
103	Hydrazine thrust to increase sep distance	0:20	0:20		0:20			0:20
104	Coast to 20 nmi	0:40	1:10		1:10			1:10
104	Prepare for burn	1:50	0:10					
105	Main Engine Start	2:00	0:10					
106	Ground/Node monitoring	2:00	4:00					4:00
107	Node hangar repair/maintenance performed	3:00	8:00	4:00	8:00			
RESOURCE TOTALS				4:00	10:18	0:00	0:00	28:18

The current mission models for the STV are in revision so the number of missions per year could range from three to ten. The lower number of missions coupled with the simpler pumping arrangement could make the reboost option desirable. The higher flight rates would make the arrangement less flexible and impractical. Tables 4-1 and 4-2 show the detailed timelines for tank delivery and STV operations for the two options. Table 4-2 summarizes the Space Station resources used to perform the STV operations.

The placement of the tanks for the microgravity, capillary device propellant transfer option is not critical. Figure 4-8 shows a potential location which has the benefit of being close to the attitude control thrusters (which may help to minimize the SS truss member stresses), and is also consistent with micrometeoroid/debris protection and Bond Number design/performance considerations. The final tank placement should be chosen based on ease of attachment, operations, and center of gravity considerations.

The tank placement for the reboost propellant transfer option is also not critical but must be designed and appropriately oriented so that settling and pumping can occur. Figure 4-9 illustrates a possible configuration for the reboost option. The "g" level required for proper settling of the fluids to support pumping is on the order of 1×10^{-4} . Figure 4-10 is a graph of the reboost duration versus altitude to be gained. The delta between any two altitudes is just the difference in time for a given g level between the two altitudes on the initial altitude axis. For example, with a reboost acceleration of 1×10^{-4} g's, the time required to reboost between 300 km and 350 km is about 8 hours. Reboosts are expected approximately every three months although it may be possible to perform smaller reboosts more frequently to facilitate STV tanking.

Due to the large quantities of cryogenic propellants needed to support the larger Code Z missions, basing the propellant depot at the Space Station to support Mars and Phobos missions were not considered in this study. This decision is based upon operations, safety, logistics, dynamics, and stationkeeping considerations.

4.2.2 PROPELLANT TANKS ON A CO-ORBITING PLATFORM. The storage of the propellant and the performance of maintenance/ resupply operations on a co-orbiting platform are also an option. The operations involved in delivering the propellant tanks to the platform are very similar to the delivery of tanks to the Station except that the control zones will not likely be as restrictive. The use of the ACEM along with the OMV is baselined, as the ability of the OMV to control such a large structure in proximity to a platform is very limited.

Table 4-2. Summary of LTCSF Delivery, Berthing, and STV Launch Operational Timelines

Event Description	EVA	IVA	OMV	RMS	Ground
Preparation of Station for Tank Delivery					
Tank Delivery	6:00	25:00	31:00	2:00	20:00
Launch of Tank	0:00	1:00	0:00	0:00	6:00
OMV Operations	0:00	8:20	18:20	4:10	14:20
MRMS Operations	0:00	26:00	24:00	23:00	26:00
STV Operations at Station					
Zero-g Propellant Transfer	4:00	44:00	0:00	22:00	106:00
Reboost Propellant Transfer	4:00	58:00	0:00	22:00	112:00
STV Deployment Operations					
	4:00	10:18	0:00	0:00	28:18
TOTAL	14:00	114-128:38	73:20	51:10	200-206:38

NOTES:

1. EVA hours are operations hours, manhours are times 2.
2. Ground hours are operations hours, manhours are times 5.
3. The TOTALs include the range of time for both the Zero-g and the Reboost Propellant Transfer. The Reboost time is the larger of the two.

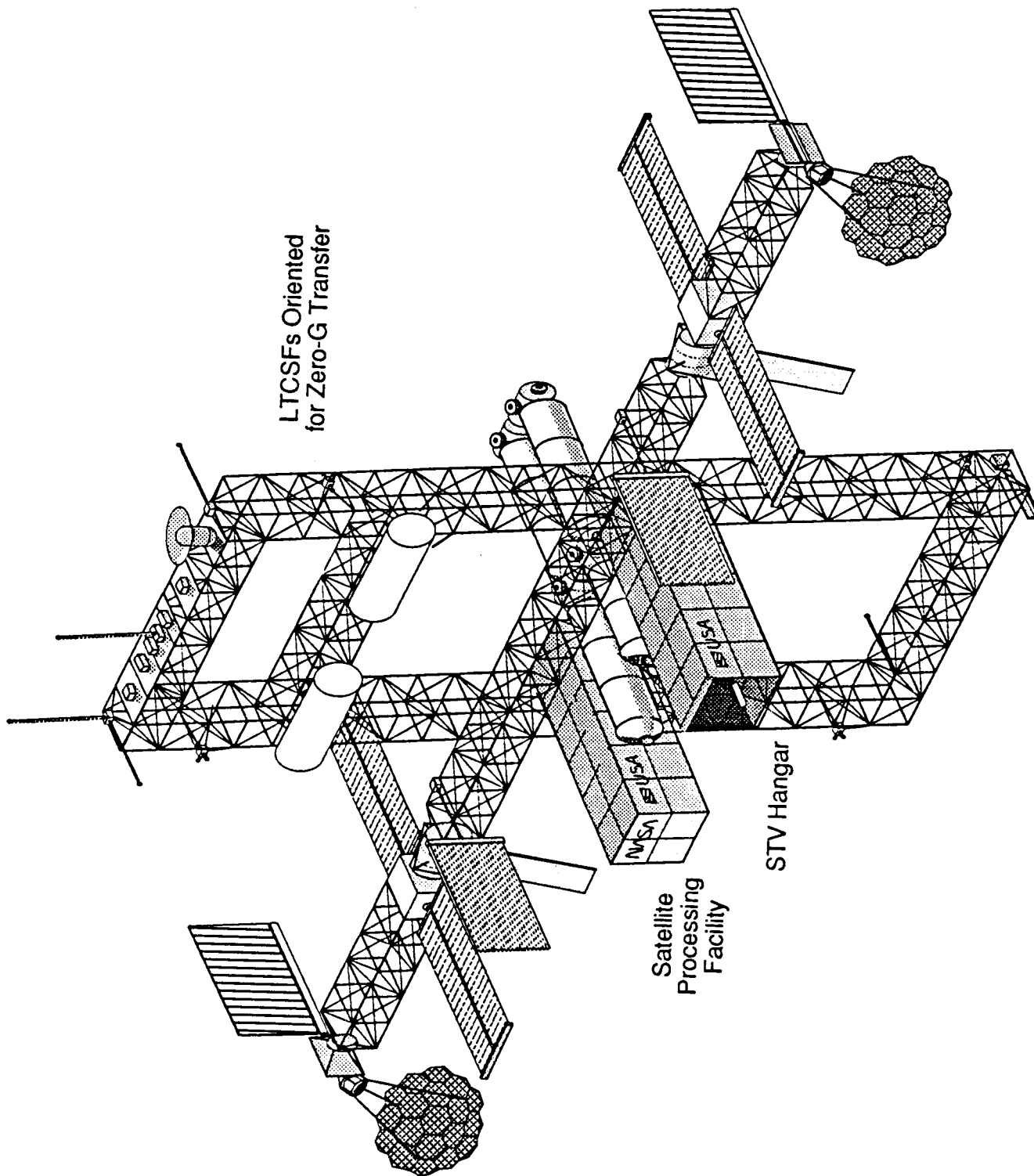


Figure 4-8. LTCSF at Space Station Configured for Microgravity Capillary Device Propellant Acquisition

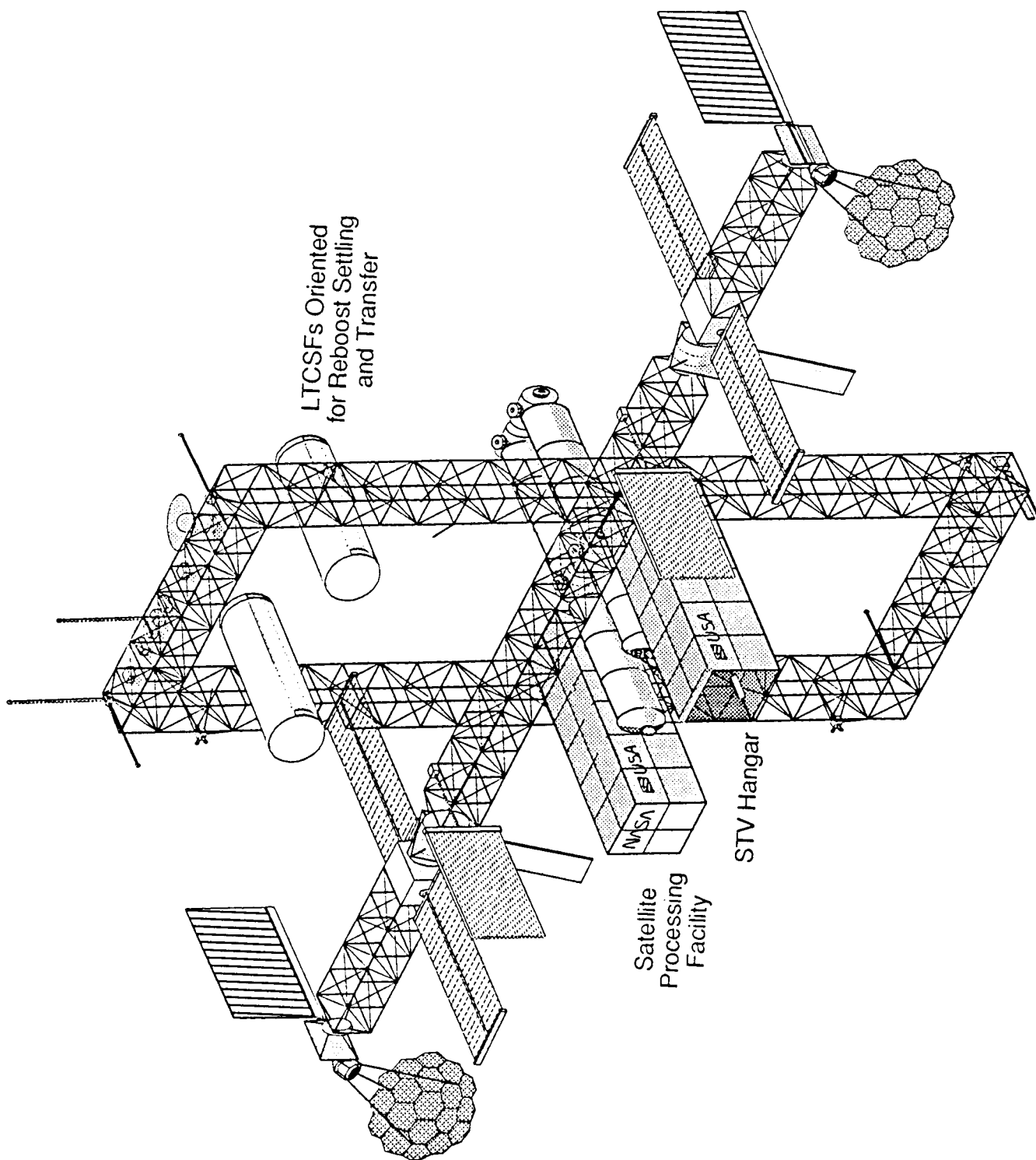


Figure 4-9. LTCSE at Space Station Configured for Reboost Propellant Settling

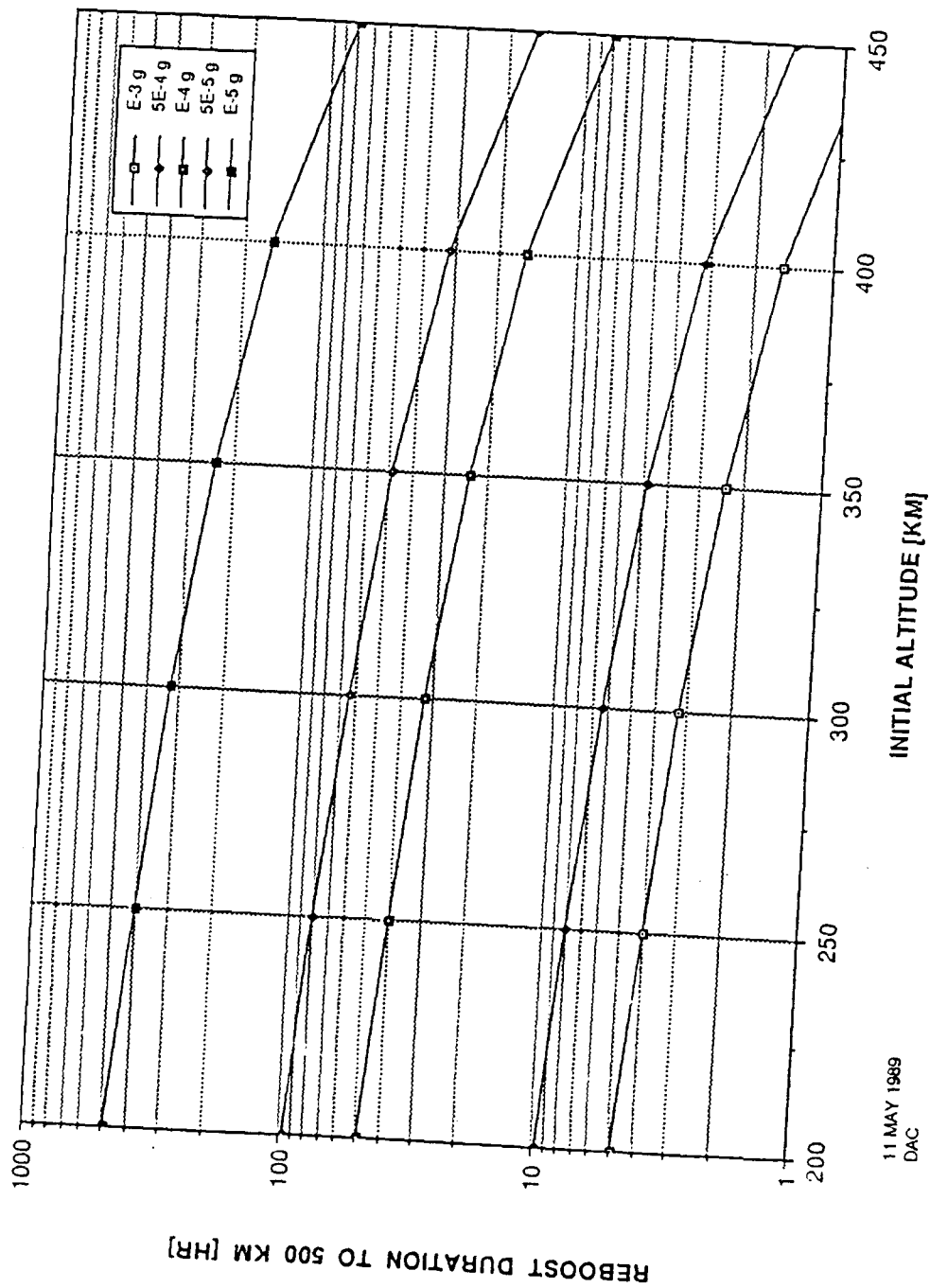


Figure 4-10. Acceleration Affects on Space Station Reboost Timelines

Additionally, the option to transfer propellant either in a microgravity environment or a reboost environment is available. The concerns and operational characteristics are very similar to those of the Station as mentioned in Section 4.2.1.

The possibility of man-tending the platform during periods of high activity or for maintenance will require the transfer of the crew either from the Station or direct delivery by the Shuttle. The baseline propellant delivery and transfer operations concepts are for remote control and telerobotics.

CAD drawings have been produced for co-orbiting refueling platforms to satisfy Code Z and M propellant requirements. Slight modifications were necessary to the LTCSF tankset design to facilitate the 7:1 burn ratios for the advanced cryogenic engines planned for Code Z.

To investigate the impact of a change of propellant with an oxidizer to fuel mass ratio of 6:1 to 7:1 on the overall size of the tankset (within its structure and micrometeoroid/ orbital debris shield design envelope) the previously designed 100klb LTCSF configuration was used as a baseline. The impact of using other tankset volumes, up to 200klb is minimal as the ACEM/OMV capability is designed for the largest tankset option. The changes were based on the following assumptions:

- Total stored propellant weight to remain the same (100,000 lbs)
- LO2 density 70.3 lbs/ft³ @ 20 PSIA
- LO2 ullage volume 3%
- LH2 density 4.33 lbs/ft³ @ 20 PSIA
- LH2 ullage volume 5%

A geometric analysis was performed to determine the changes required in tank sizes for the new ratio. This resulted in a stored propellant weight increase for the LO2 of 1,786 lbs and a weight decrease for the LH2 of the same amount (since the total weight must remain the same).

Next, the changes in volume were calculated giving a volume increase for the LO2 of 25.4 ft³. For 3% ullage the total change in volume would be 26.2 ft³. The calculated volume change of LH2 is 412.5 ft³. For 5% ullage the total change in volume would be a decrease in volume for the LH2 tank of 430.1 ft³.

Finally, the changes in tank sizes as related to the cylindrical section were determined. To

accommodate the decreased LH2 volume, the cylindrical section length must be reduced by 3.33 ft or 39.9 inches and the LO2 tank cylindrical section length would be increased by 0.2 ft or 2.4 inches, to accommodate the increase in stored LO2.

Five co-orbiting propellant storage depot concepts have been defined based on the 100,000 lb. size LH2/LO2 storage concepts. These were presented in Figures 3-9 through 3-14. Each depot concept provides propellant provisioning for each Code Z and STV Mission Model, with additional propellant to account for losses, provide a safety margin, and to provide a minimum propellant inventory at all times.

For example, the free flying co-orbiting concept to provide propellant for the Mars Expedition model shown in Figure 3-12 is based upon the peak requirement for thirty-two 100,000 pound tanksets at the year 2006. It has tanksets mounted on both sides of the basic platform structure which can be accessed by the MRMS's mounted along the structure. There are three arms which can each travel on one planer surface without having to turn any corners and an additional arm is specified in order to unload tanksets from a docked orbiter bay (if tanksets are launched empty) or from an ACEM/OMV (if the tanksets are launched full, and delivered by an expendable vehicle).

The basic depot itself is based on the 900,000 lb storage capacity orbital refueling platform concept as defined in Reference 1-4. All of the orbital depot concepts are based upon "modular " construction using integral numbers of tanksets attached to a 5-meter truss structure. In addition to the LTCSF tanksets on each platform, there are mission peculiar (i.e. hydrazine) required storage containers shown on some.

4.3 BASELINED OPTIONS SUMMARY

Both experimental and vehicle fluid management approaches for the IOC and growth Space Stations have been presented.

Preferred concepts and corresponding transfer and delivery operations have been presented for STV propellant provisioning from the SS, based on; 1) STV mission model propellant requirements, 2) reboost liquid settling and microgravity propellant acquisition methods. These scenarios used the OMV/ACEM concept, developed for this study, to translate and dock the LTCSF propellant tankset from LEO to the SS. Reboost and microgravity (or surface tension/capillary action) settling methods result in comparable overall transfer operation elapsed time, but the reboost method may have a detrimental effect on SS users/operations, depending on the mission model and the associated

propellant use schedule.

Provisioning methods of meeting experiment fluid requirements using three fluid carrier design concepts have been presented, beginning on the IOC SS with the replacement of ORUs and evolving into integrated fluid subsystems/fluid docking interfaces on the growth SS. Assembly layouts of the IOC and growth SS have been presented to indicate a possible working configuration to accommodate all fluid users.

4-5
4-6

5

SPACE STATION IMPACTS

Several design features and capabilities should exist on the Phase I SS to meet current and growth fluid management requirements between 1994 and 2016 and beyond. Preliminary hooks and scars have been determined for the Phase I SS to accommodate growth.

The following six (6) Safety Design Considerations for the development of an overall Fluid Management concept for the Space Station were considered for the concepts developed during this study:

1. Separate Fuels and Oxidizers
2. Minimize ExtraVehicular Activity (EVA)
3. Design for expedient EVA
4. Protect internal/external depot components from contamination
5. Protect experiments from contamination
6. Plan for spills/leaks (develop de-contamination procedures for equipment and EVA suits).

To support experimental fluid and propellant provisioning operations there are many design implications on the Space Station.

There must be truss structure space allocated for several fluid carriers. In addition, there must be attachment fittings for the mechanical connection/docking of the fluid carriers. Truss structure beam strengthening (or the scarring of the baseline SS truss member design) must be provided where it is determined by structural analyses to be needed. This is due to the attachment of large (100 klb. to 500 klb.) propellant storage tanksets, and the higher resulting stresses which may occur in the truss structure during SS attitude control/reboost.

The mechanical and fluid interface panels for the fluid carriers and propellant tanksets should have remote connect/disconnect capability to allow telerobotic RMS activities, which must include electrical

connections for power, data monitoring and control. The logistics carrier interfaces on the baseline SS should be designed to accommodate and be compatible with Growth SS needs (i.e. fluid carriers, integrated fluid subsystems, and propellant tanksets).

The SS must have a Mobile Remote Manipulator System (MRMS) for fluid carrier and experiment activities. The use of two MRMSs are recommended, due to propellant tankset handling requirements, and the SS requirement that the "payload be captured at all times". The MRMSs could be used to:

- unload fluids carriers from the Shuttle (or ELV) and integrate them with SS truss structure
- transport fluid carriers, bottles, tanks, experimental payloads and EVA astronauts
- perform and/or aid astronauts in replenishment activities (e.g. ORUs, buildup of Integrated Fluid Subsystems, capturing/docking of free-flying payloads, etc.)
- hold several ORUs simultaneously during EVA/IVA to economize "operations"

To use the MRMS for attached experimental payload servicing on the SS, the MRMS must have accommodations for holding full and empty experiment fluid reservoir tanks/bottles so that the arm can be free to perform other activities.

The IOC INS should have the correct fluid interface and software "hook" to allow the addition of new, perhaps larger N2 storage tanks.

The SS attitude control and reboosting capabilities must be designed for a growth in SS mass, and considerable changes in the center of mass of the SS.

5.1 CODE Z MISSIONS

Space Station impacts for Code Z mission fluid management activities will be minimal. As mentioned earlier, the large quantities of propellant required to support the Code Z missions, makes storage of these propellants at the Station unlikely. For the purposes of this study, co-orbiting depots were used to fulfill Code Z propellant requirements. Operations at these co-orbiting depots (see Section 3.3) could be done remotely from the ground and therefore there is little impact on the Station.

For man-tended operations the Station will be needed for the human accommodations, supplies and medical facilities. If these depots are man-tended from the Station, as opposed to the Shuttle, a crew transport vehicle will be needed to ferry crew members back and forth. The Station would be required

to have storage and refurbishment accommodations for this vehicle.

5.2 STV MISSIONS

Propellant Tanksets Attached to the Space Station

In order to support the STV missions from the Station there must exist the capability to deliver, store and transfer propellant. As mentioned earlier, the LTCSF designs for cryogenic propellant storage at the Station were used in this study. For placement of these tanksets on the Station there must be space allocated along the truss and attachment fittings. Beam strengthening should be used where needed. In addition, there must be fluid, power, data, and control lines connecting the tanksets to the Station control center and to the STV Hanger. This would be accomplished with an interface panel such as those shown in Figure 4-1 (Section 4).

The SS attitude control system must be capable of handling the SS with between 100 and 500 klb. of additional weight due to STV propellant storage tanksets. Growth SS aerodynamic drag, center of mass, structural, and reboost thrust levels/schedule must all be considered in the Baseline SS attitude control system design.

Due to the size of the tanksets (i.e. 200klb capacity tanksets) there must be two MRMSs available to capture the tankset, move it to its attachment point and secure it. The simultaneous operation of two MRMSs will require specialized software "hooks" in the IOC to accommodate upgrades to handle these coordinated tasks.

Software is needed for propellant tankset delivery operations, to monitor the propellant tank status, and control all thermodynamic processes, including propellant prechill and transfer. This should involve some level of artificial intelligence to free the astronauts from routine monitoring activities, and minimize the requirement for human interaction/supervision.

To deliver the tanksets to the Station an OMV and an ACEM will be needed. The Station must provide a servicing bay and storage facility where both pieces of equipment can be refurbished and protected. A control station must be made available in the pressurized module to allow an astronaut to perform OMV/ACEM activities. Although this could be done from the ground, it is more likely that anything entering the Space Station proximity operations zone will have to be controllable from the Station.

For STV storage, servicing and payload integration there must be a STV Hanger. This hanger must have power, data and control lines, servicing equipment and propellant transfer lines running from the tanksets.

Co-Orbiting Refueling Platform

A co-orbiting depot for STV mission support will have the same minor Space Station impacts as the Code Z depots (see Code Z above).

5.3 REQUIRED EMERGING AND ENABLING TECHNOLOGIES

There are several technologies that are required for the realization of cryogenic and storable fluid storage, acquisition, and transfer in the LEO environment.

Fluid Disconnects

Cryogenic and storable fluid disconnects which may be mated by telerobotic operations will be necessary to minimize EVA for fluid carrier delivery and transfer operations. Low-leak fluid disconnects have been developed for space applications, but are only designed for non-cryogenic fluids. Both storable and cryogenic fluid disconnects should be designed to be part of a fluid/power/data berthing panel, which would provide all of the necessary interfaces between the user and either the SS or a co-orbiting platform.

Space -Qualified Refrigeration Systems

For propellant storage at the SS, if no venting of oxygen or hydrogen boiloff is allowed, a refrigeration system must be used to condense all boiloff, and return the propellants to storage temperature and pressure. While there has been a considerable amount of research in the last 10 years concerning space-qualified cryogenic refrigeration, high capacity units suitable for hydrogen reliquifaction have not been tested in space.

Cryogenic Valves, Pumps, Compressors

The required flight-qualified components for the control of all storage and transfer functions within a propellant storage tankset are not all presently available. Low flow rate Joule-Thompson valves, check valves, low head/flowrate pumps, and high pressure gas compressors designed for low maintenance applications will be needed.

Instrumentation

The instrumentation requirements for propellant and other fluid storage tank monitoring and process control are unique due to the lack of substantial gravity. Two-phase flow, mass gauging, and leak detection for microgravity, low pressure environments are not readily available.

6

CONCLUSIONS AND RECOMMENDATIONS

The Phase I Space Station, known as Freedom, is regarded as an essential element of NASA's continuing effort to ensure America's future in space. The station is required to allow more complete human exploration of the solar system. The station will also be an orbiting research laboratory for science, technology, and commercial space development. The Phase II or evolutionary Space Station (growth version of Phase I) may be used for a variety of purposes in support of NASA's Lunar, LEO, Mars and other space exploration missions. The primary purpose of this study was to define fluid storage and handling strategies/requirements for various specific mission case studies and their associated design impacts on the Space Station.

Several observations can be made regarding SS related fluid requirements. First, there are a variety of fluid users which require a variety of fluids and use rates. Secondly, the cryogenic propellants required for NASA's STV, Planetary, and Code Z missions are enormous. The storage methods must accommodate fluids ranging from a high pressure gas or supercritical state fluid to a subcooled liquid (and superfluid helium). These requirements begin in the year 1994, reach a maximum of nearly 1800 metric tons in the year 2004, and "trail off" to the year 2018, as currently planned.

The preliminary definition of "Hooks and Scars" to the Phase I Space Station to accommodate fluid management requirements between 1994 and 2016 (and beyond), to be supported partly by the Phase I SS, has been completed and documented. As experimental fluid needs grow, they will be met by the delivery of fluid carriers to the SS, and possibly the construction of integrated fluid subsystems for each fluid (similar to the INS already planned for the IOC SS).

In providing the SS attached experiments with required fluids, preliminary comparisons have shown that the best method utilizes hard fluid lines between each user and a manifold /disconnect panel to which each fluid carrier is docked. This capability, however, is not needed at the IOC SS (which provides the wide range of fluid use rates/users with fluids via ORU changeout, and bulk LHe replenishing in the case of ASTROMAG) and should only be used for the growth SS if operational and economic benefits are shown to exist.

For the experiments which are not attached to (but will receive fluid servicing from) the SS, hard lines are obviously unacceptable. Since the recommended growth approach for the attached payloads

uses hard lines within an integrated fluid subsystem architecture, refilling of the unattached payloads while they are docked to the SS could be accomplished through an additional fluid/docking interface.

The ASTROMAG experiment is a major user of LHe. A dedicated LHe storage dewar system concept, resupplied by the STS or ELV tanker, is recommended. A number of dewars could be incorporated into a LHe fluid carrier concept similar to the one shown in Figure 3-2, and be used to provide AXAF, LDR, and SIRTf LHe needs as well. The unattached LHe experiments could be docked in the CSF near the LHe carrier, connected to it by hard transfer lines using "quick disconnect" fluid lines and other required support equipment, and refilled while receiving other required servicing from the CSF.

It is conceivable that the cryogenic propellant needs for the STV and/or Lunar mission models will be met by LTCSF LH2/LO2 tanksets attached to the SS truss structure. Concepts and corresponding transfer and delivery operations have been presented for STV propellant provisioning from the SS. For STV storage, servicing, and payload integration there must be an STV hanger, and servicing, power, and propellant transfer lines/disconnects.

Due to the large LH2 and LO2 quantities involved, unmanned co-orbiting refueling platforms have been conceptually designed, which are based on LTCSF storage tankset technology for Code Z, Planetary Initiative, and possibly STV mission models.

Preliminary thermodynamic analyses of tankset processes have been presented. Results indicate that a 100klb capacity tankset LH2 tank can be prechilled and filled in less than 12 hours. LO2 tank prechilling and filling may be done in less than 5 hours. The steady-state boiloff rates for LH2/LO2 for the 100 and 200klb tanksets have been reported for a range of environments, and are all less than 0.4% per month by weight (combined LH2/LO2). Required ullage pressurant quantities for transfer of 7500 lb of LH2 from a storage tankset into a user tank (i.e. STV vehicle) have been estimated.

The ACEM and associated servicing capability will be required to move tanksets from delivery launch vehicles to the SS or co-orbiting platforms. Also, appropriate changes to the software used for OMV operation are necessary to allow for the combined operation of the ACEM/OMV.

Reboost settling is not recommended as a baseline mode of operation. Reboost operations of the SS could be scheduled to provide acceleration levels required for "settled" transfer of LH2/LO2 from the SS to an STV propellant tank. However, there are many other issues that need resolution to allow STV propellant provisioning from the SS, such as SS truss structure dynamics, safety, guidance,

navigation, and control issues.

To support fluid management activities at the Space Station for the experimental payloads and propellant provisioning, there must be truss structure space allocated for fluid carriers and propellant tanksets. Substantial beam strengthening may be required. In addition, there must be power, data and fluid transfer and control lines, and the SS attitude control system must be designed to facilitate changes in SS mass and center of mass/drag.

The Station must have two Mobile Remote Manipulator Systems (MRMS) and the ACEM for propellant handling operations for the STV at the SS. The two MRMSs must have accommodations for holding full and empty experiment fluid reservoir tanks/bottles, which will also require associated software capabilities.

Propellant needs for the Planetary Initiatives and Code Z mission models will most likely be provided by co-orbiting propellant platform(s). Space Station impacts for Code Z mission fluid management activities will be minimal. For man-tended operations the Station will be needed for the human accommodations. If these depots are man-tended from the Station, as opposed to the Shuttle, a crew transport vehicle will be needed.

The cryogenic LH2/LO2 propellant systems developed under NASA-MSFCs LTCSF Study were used as baseline elements for the propellant depot platforms specified in this study. A family of "evolvable" refueling platform concepts were defined to meet the STV and Code Z mission model requirements. Each platform concept has a capacity appropriate for propellant requirements, with a conservative margin. Software will be needed to monitor the tank status, and to control all modes of operation.

There are a number of safety issues that deserve attention, since ultimately the SS must provide a safe environment for human inhabitants. Spills, contamination, structural design to minimize the possibility of explosions of fluid vessels, safe quantity, and separation distances appear to be the primary safety concerns identified during this study. It is not possible to define many of the design features necessary to comply with these concerns until definitive, appropriate NASA standards have been established for SS safety and operations.

It is imperative that cryogenic propellant storage technology issues be addressed and resolved to allow for the successful completion of NASA's objectives through an integrated infrastructure.

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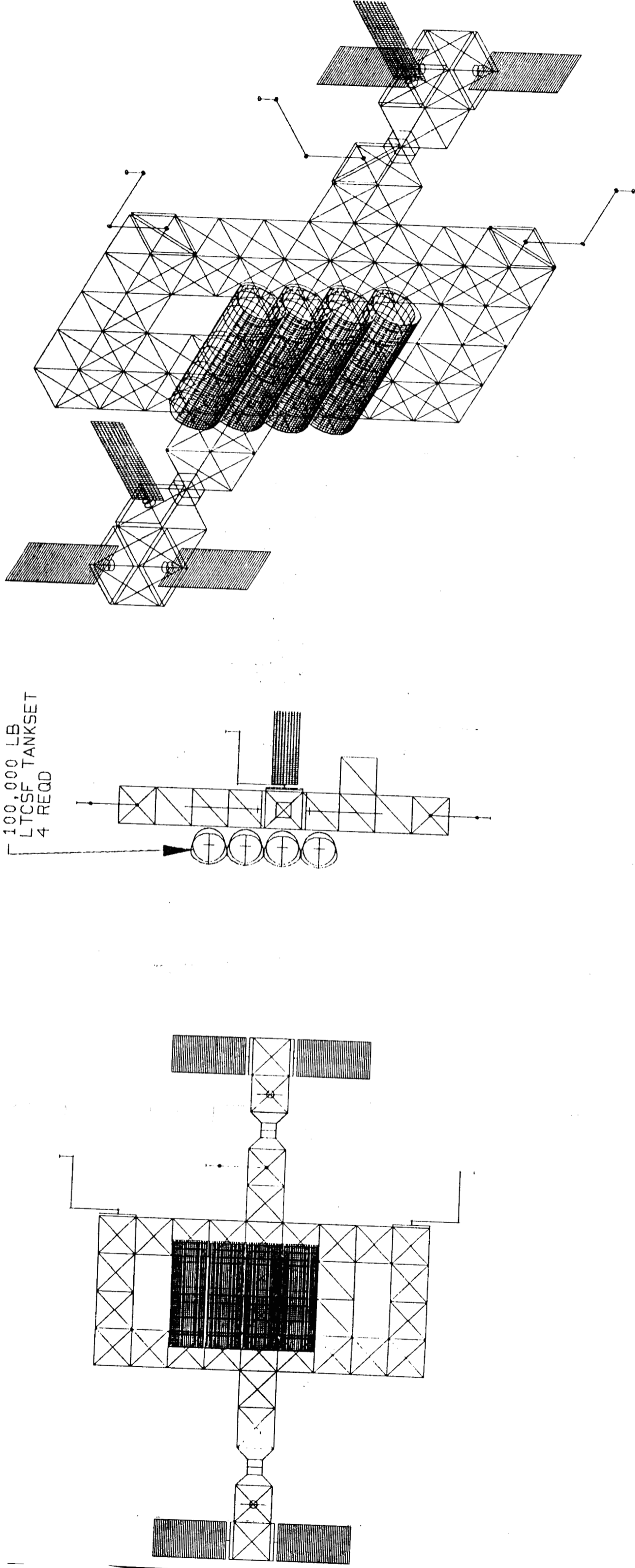
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100,000 LB
LTCSF TANKSET
4 REQD



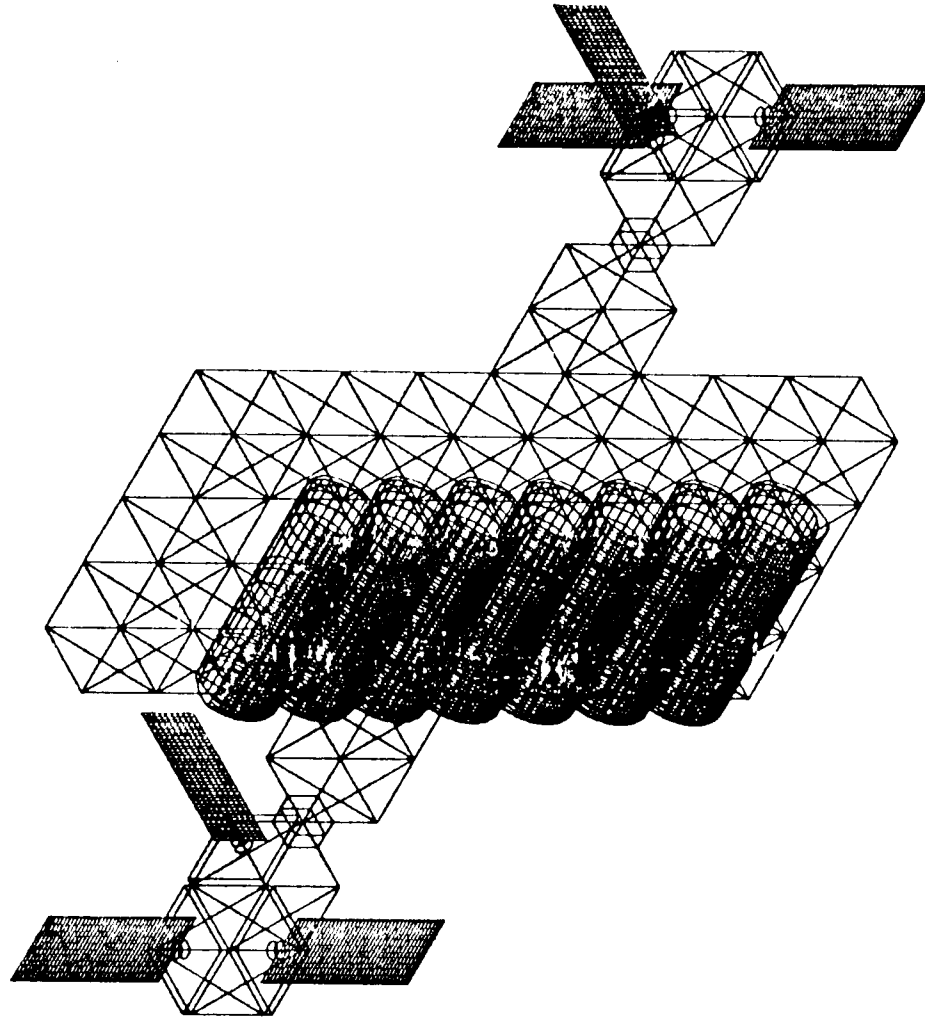
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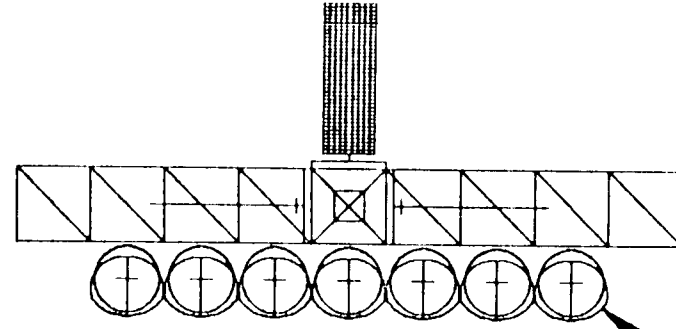
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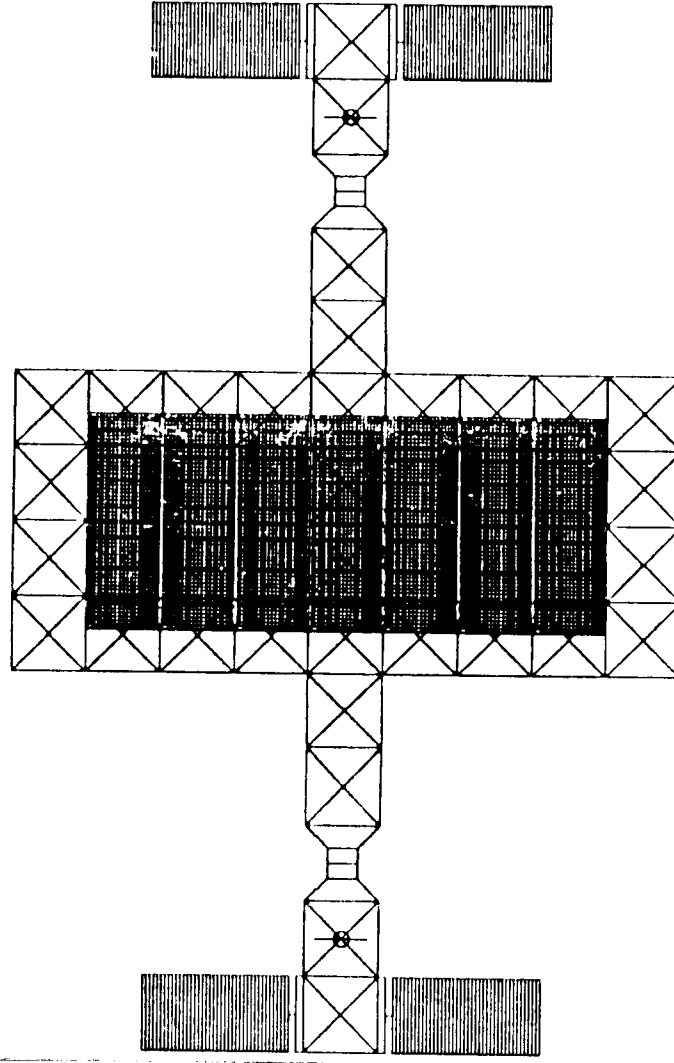
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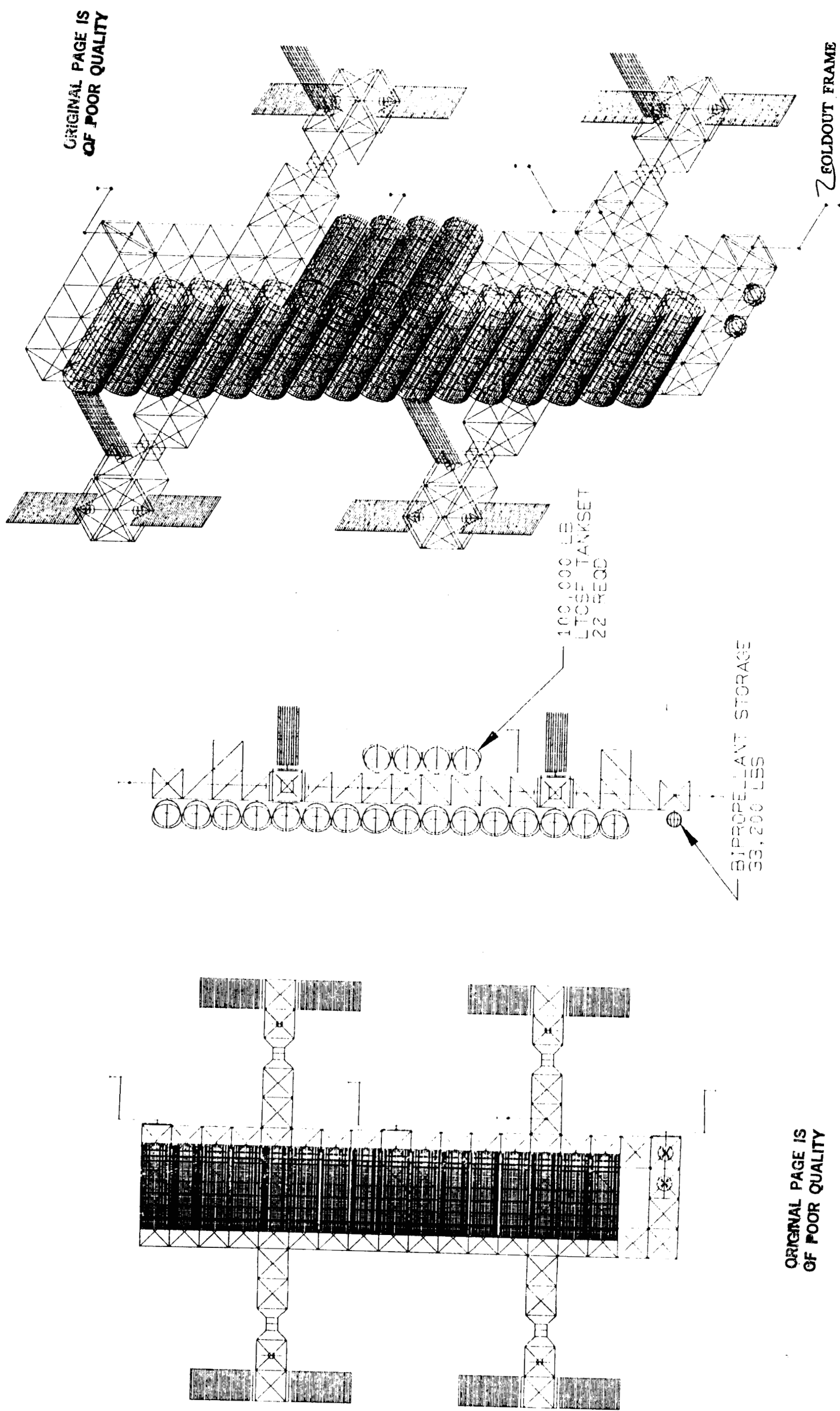


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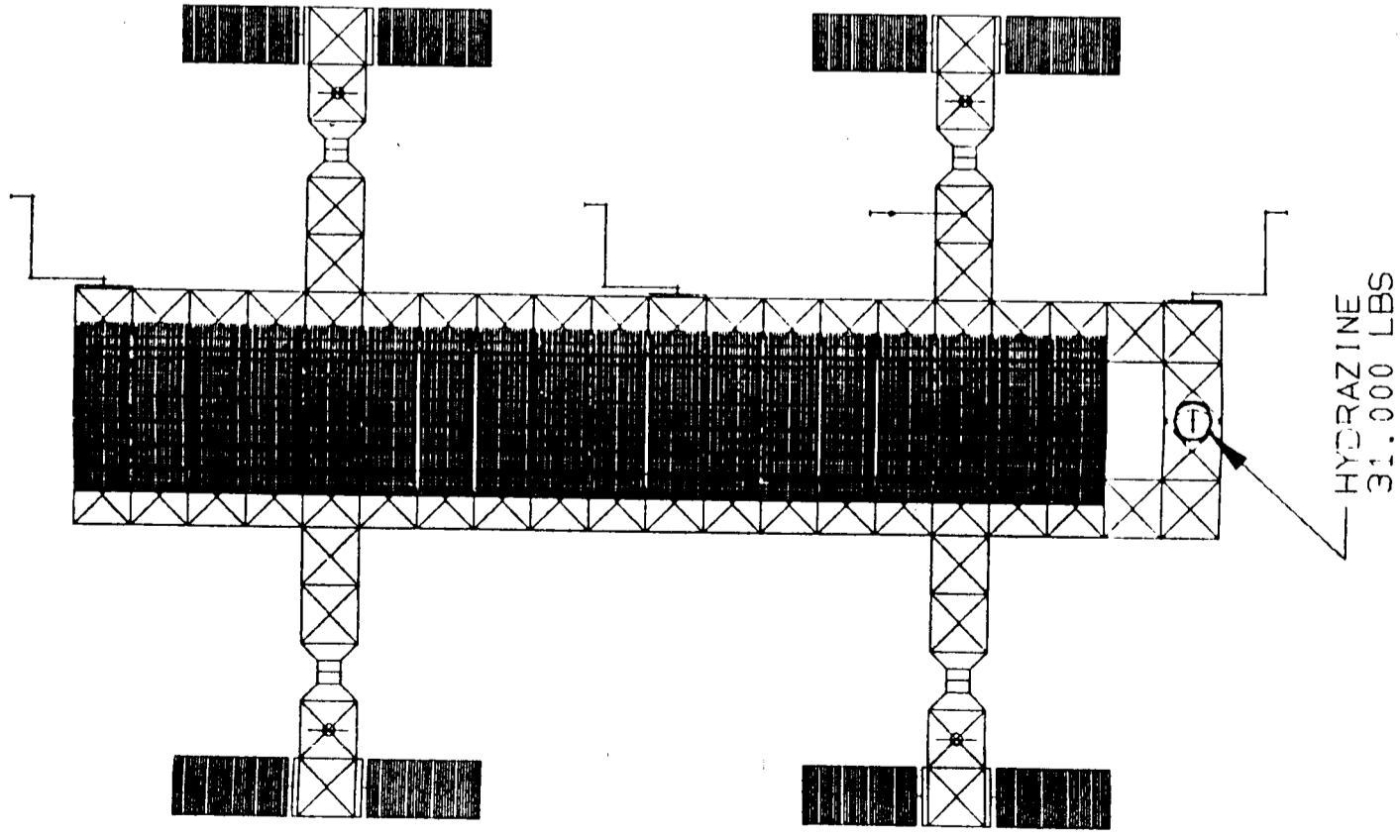


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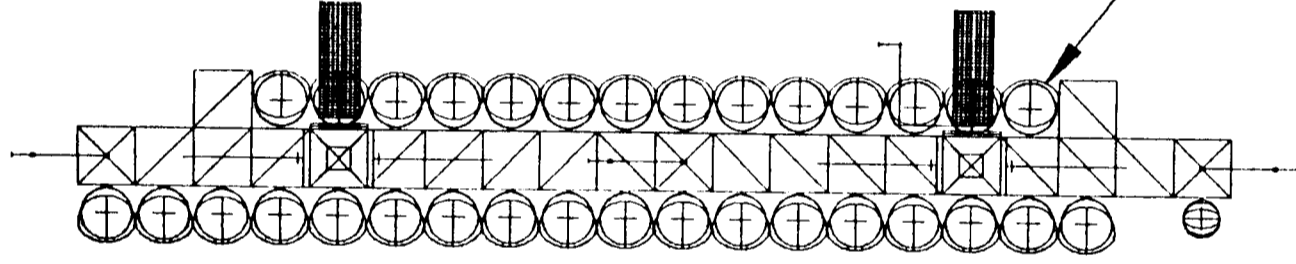
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Figure 3-11. Orbital Depot for Manned Phobos

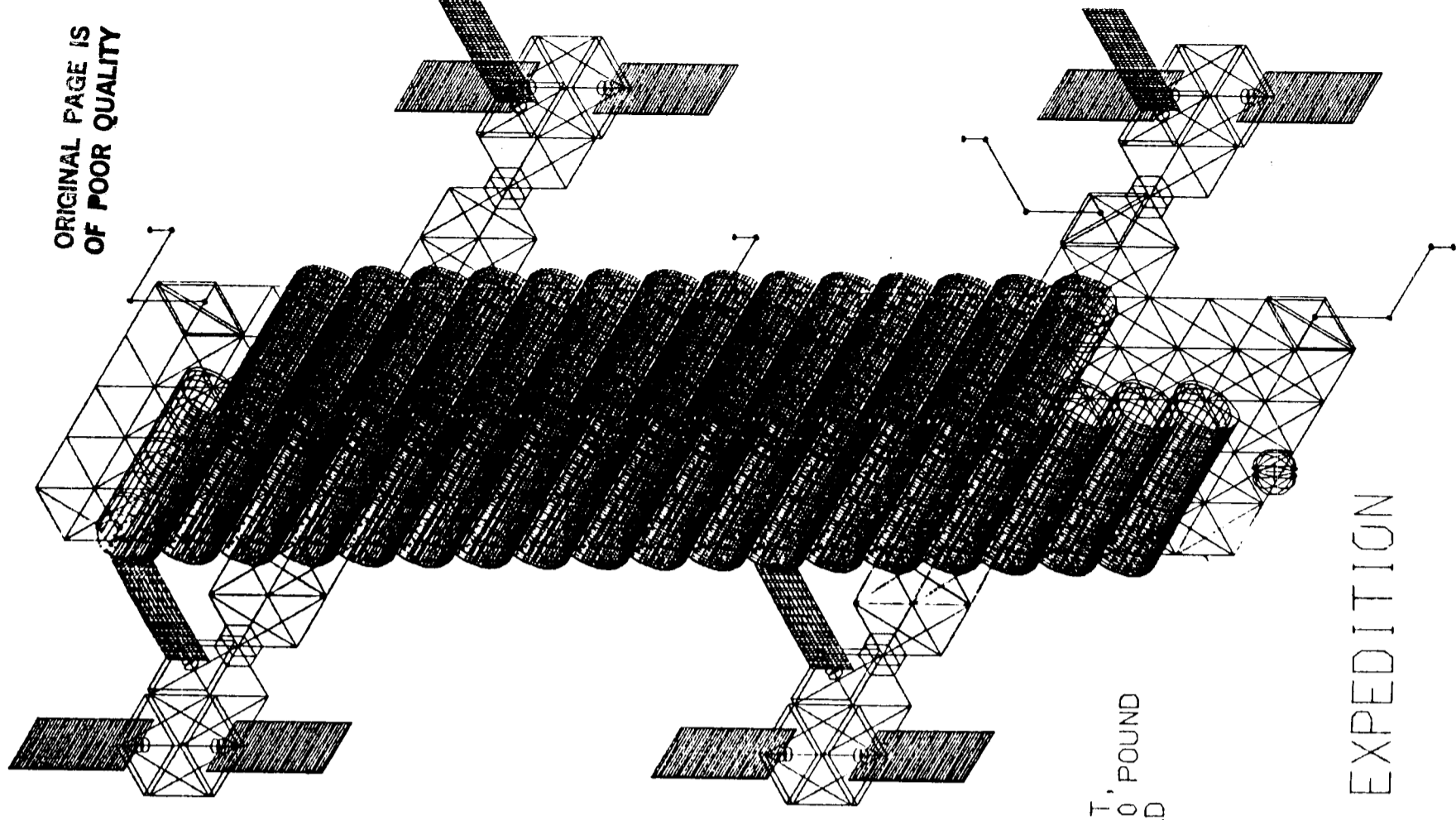
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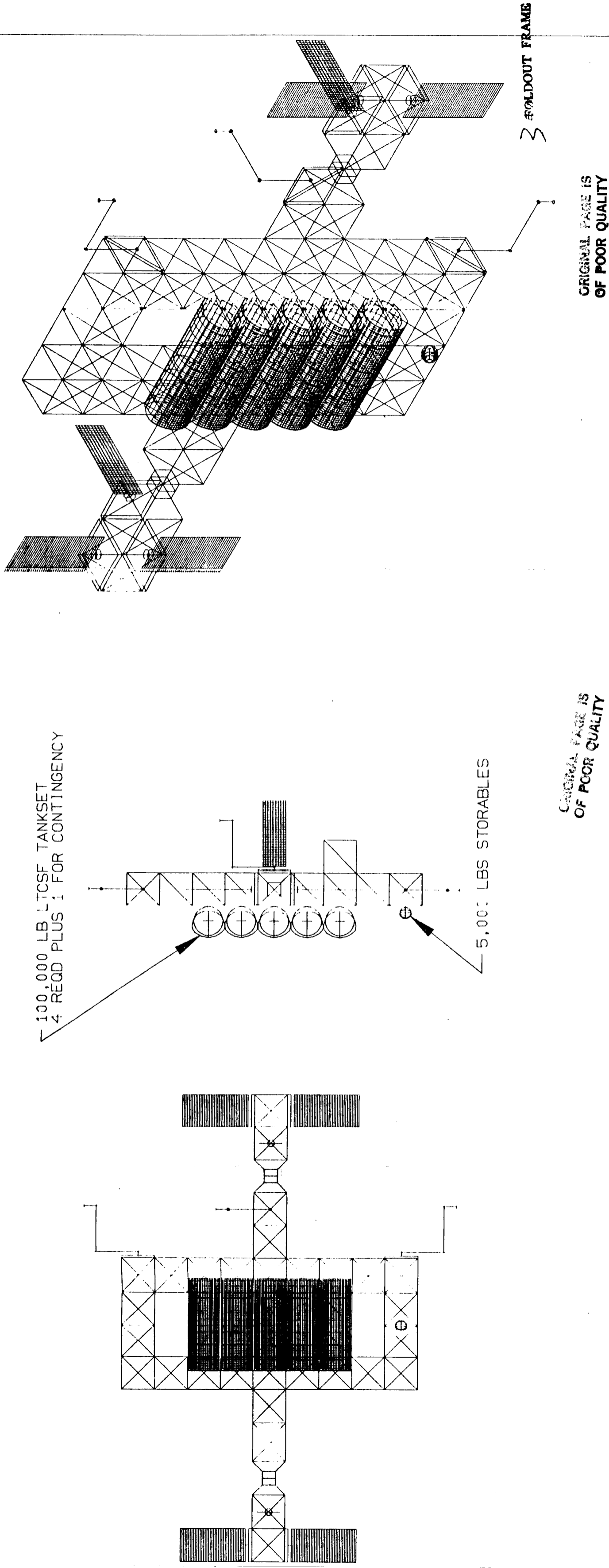
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100,000 POUND
32 REQD



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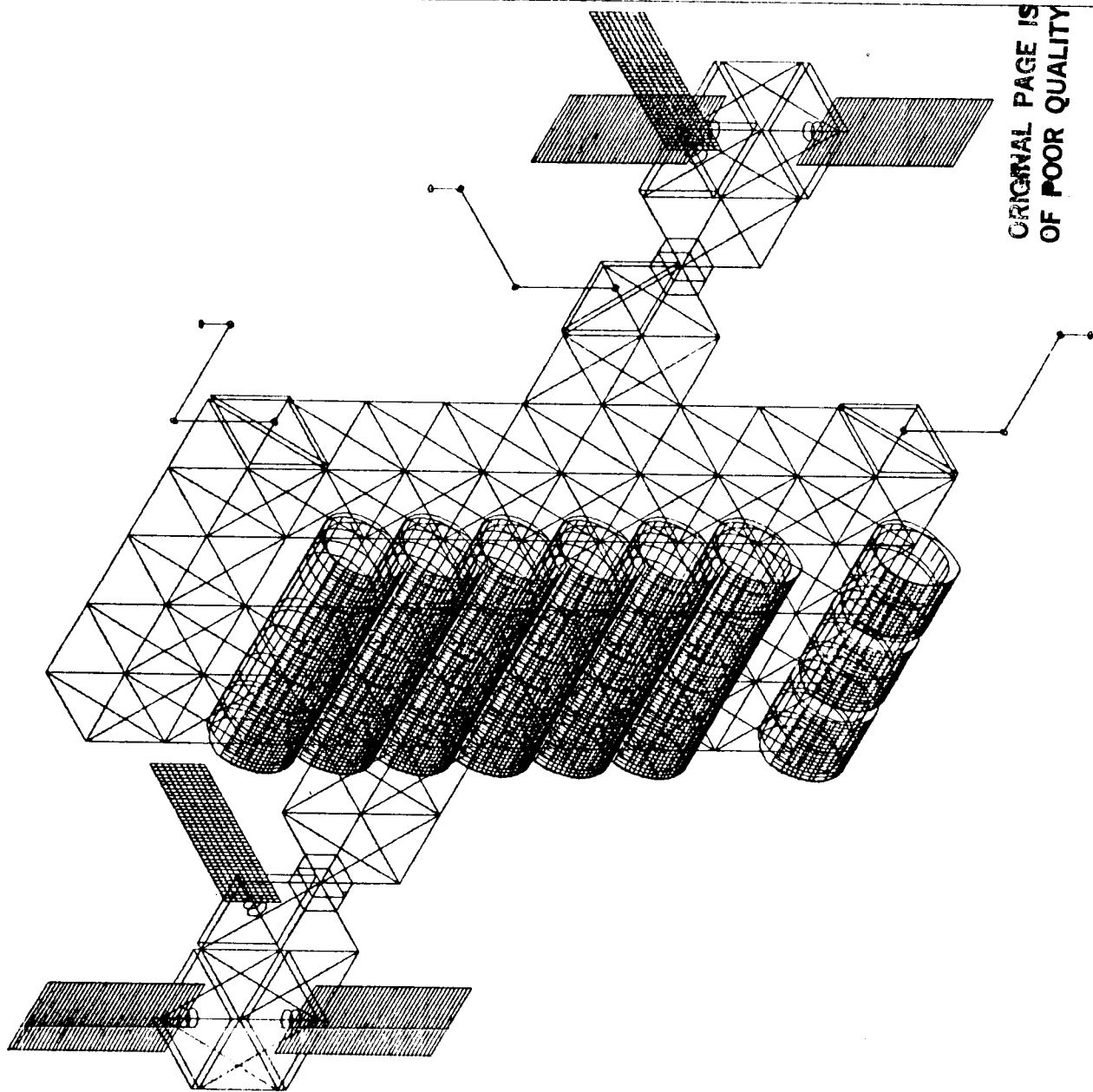
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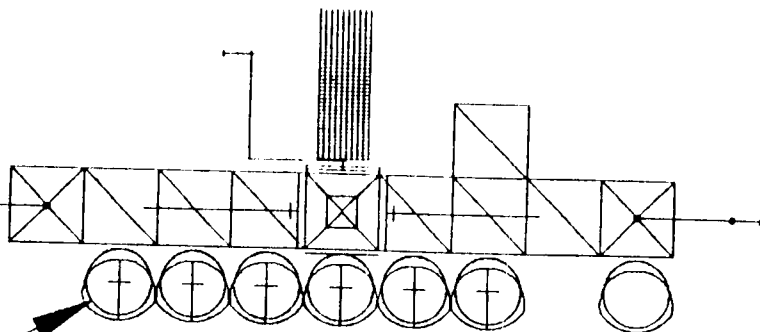
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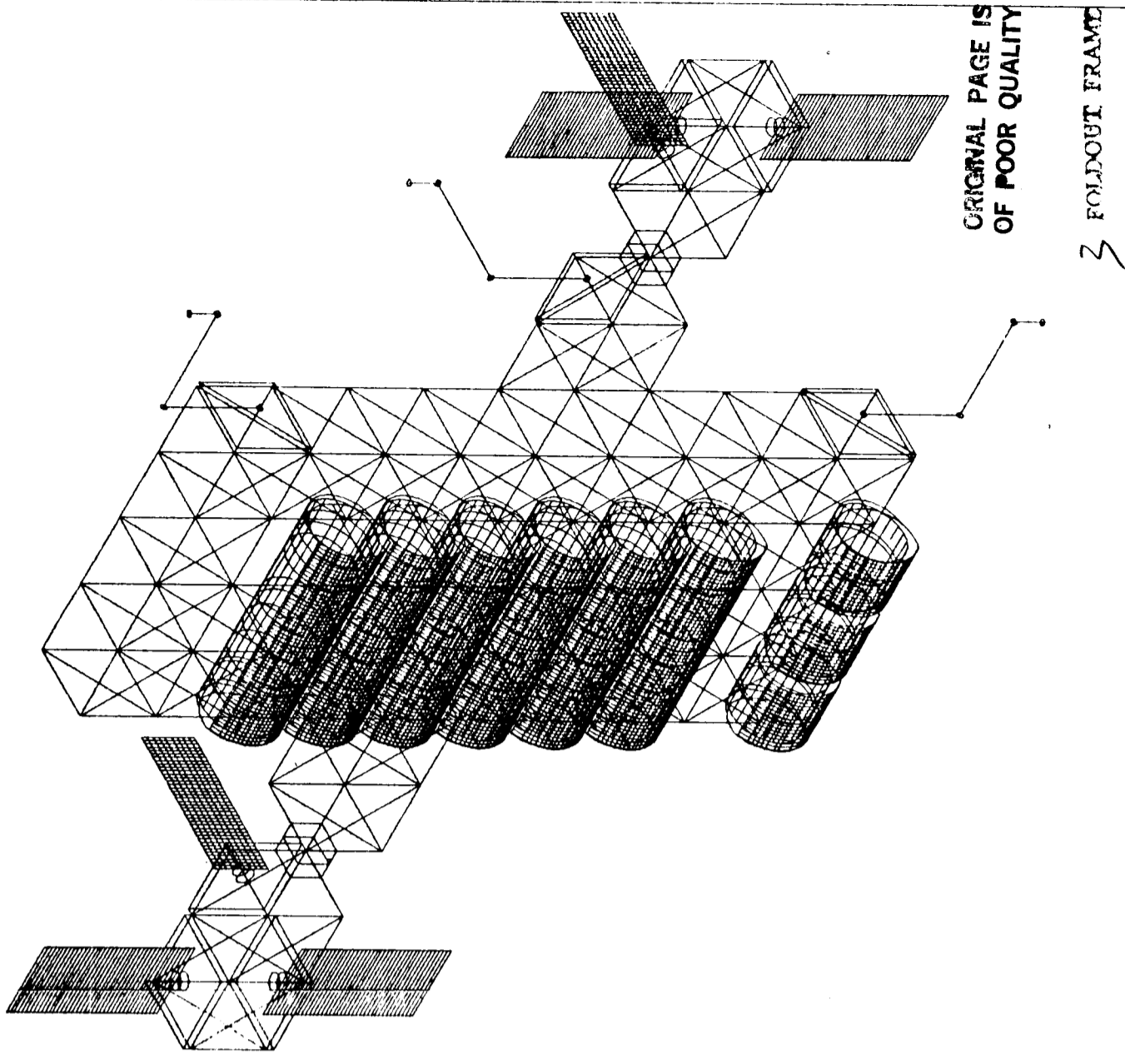
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100,000 LB LTCSF
TANKSET, 6 REQD



ARGON
AINERS
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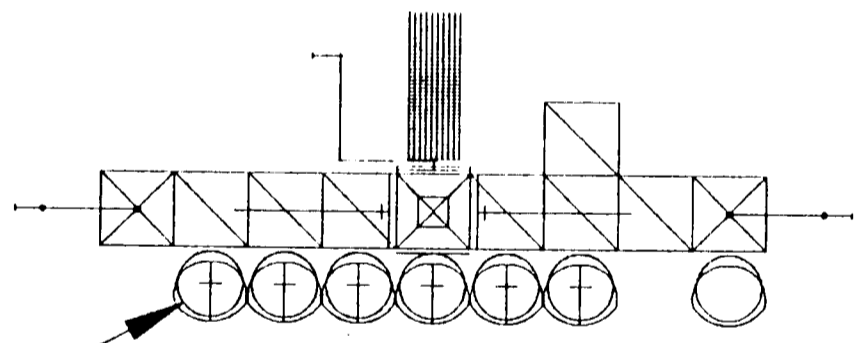
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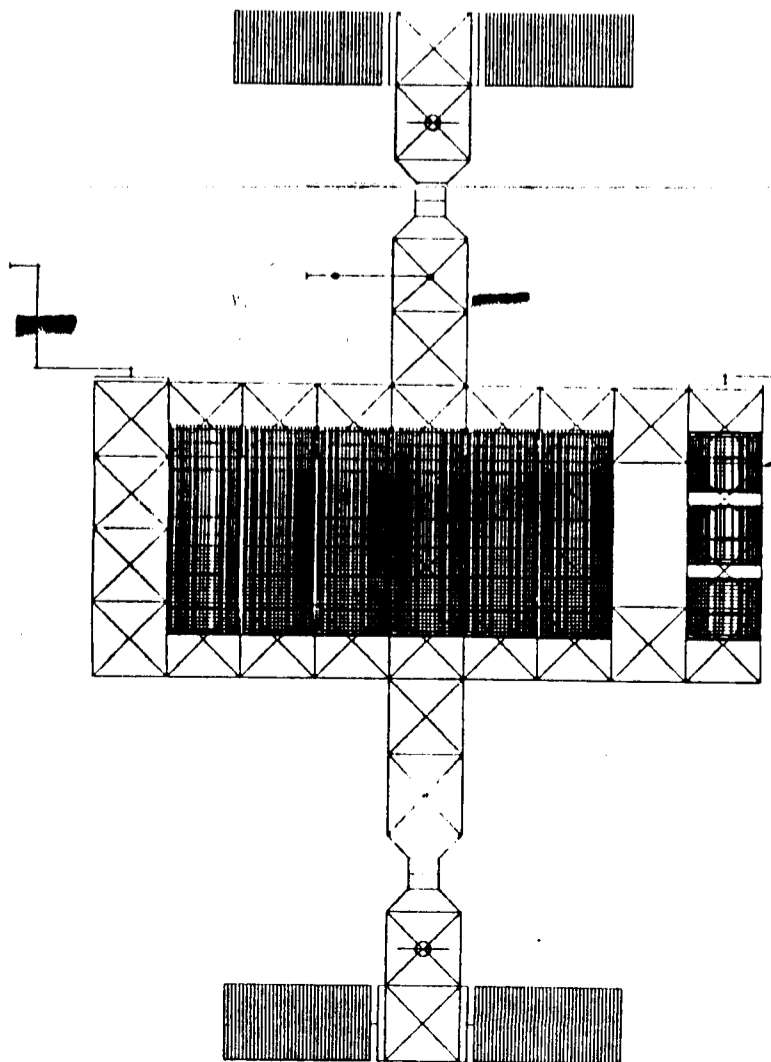
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100,000 LB LTCSF
TANKSET, 6 REQD



LIQUID ARGON
3 CONTAINERS
270,000 LBS



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Report Documentation Page

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16. Abstract <p>This report summarizes the results of an 11-month study to define fluid storage and handling strategies/requirements for various specific mission case studies and their associated design impacts on the Space Station. There are a variety of fluid users which require a variety of fluids and use rates. Also, the cryogenic propellants required for NASA's STV, Planetary, and Code Z missions are enormous. The storage methods must accommodate fluids ranging from a high pressure gas or supercritical state fluid to a sub-cooled liquid (and superfluid helium). These requirements begin in the year 1994, reach a maximum of nearly 1800 metric tons in the year 2004, and "trail off" to the year 2018, as currently planned. It is conceivable that the cryogenic propellant needs for the STV and/or Lunar mission models will be met by LTCFS LH2/L02 tanksets attached to the SS truss structure. Concepts and corresponding transfer and delivery operations have been presented for STV propellant provisioning from the SS. A "growth OMV" and associated servicing capability will be required to move tanksets from delivery launch vehicles to the SS or co-orbiting platforms. Also, appropriate changes to the software used for OMV operation are necessary to allow for the combined operation of the growth OMV. To support fluid management activities at the Space Station for the experimental payloads and propellant provisioning, there must be truss structure space allocated for fluid carriers and propellant tanksets, and substantial beam strengthening may be required. The Station must have two Mobile Remote Manipulator Systems (MRMS) and the growth OMV propellant handling operations for the STV at the SS. Propellant needs for the Planetary Initiatives and Code Z mission models will most likely be provided by co-orbiting propellant platform(s). Space Station impacts for Code Z mission fluid management activities will be minimal.</p>					
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